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By C. A. Kodres

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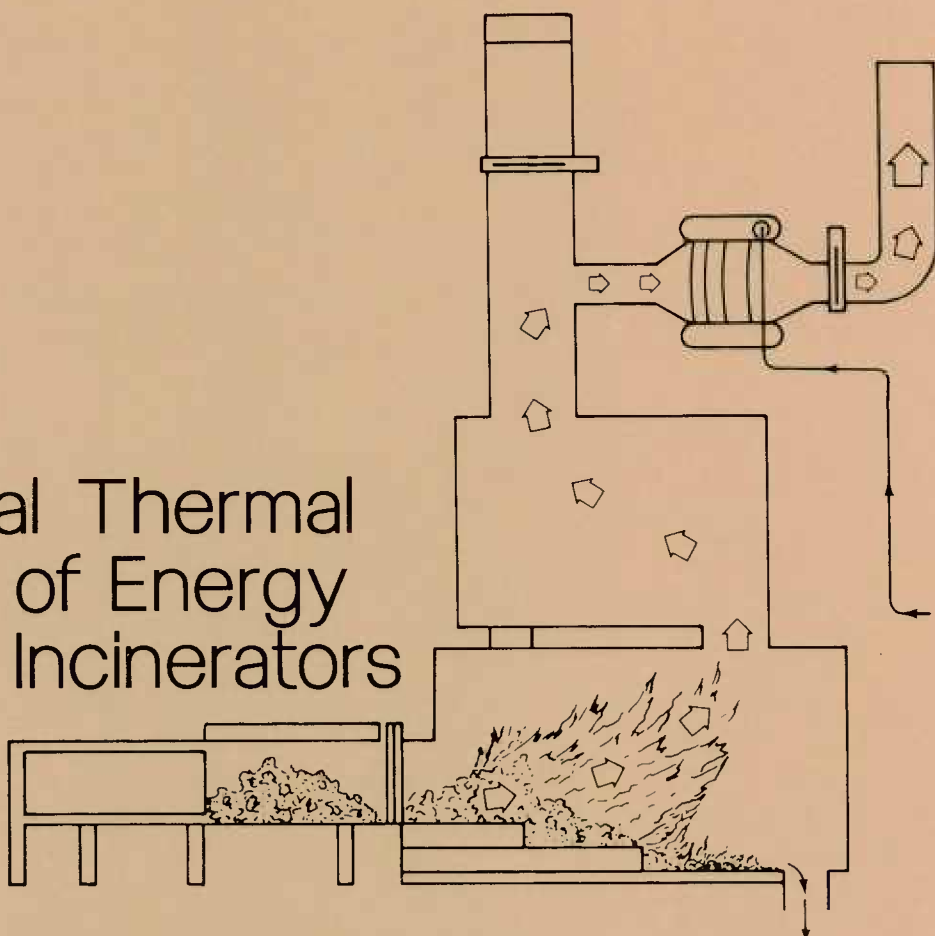


Theoretical Thermal Evaluation of Energy Recovery Incinerators

This report documents a theoretical thermal evaluation of several energy recovery incinerators. Both parametric examination and, to the extent possible, direct comparison are included. The procedure followed is to model the incinerator mathematically, use a computer program to solve the governing equations, and apply this model to make the evaluations. The incinerators studied are the smaller, about 24-tpd devices. Energy recovery is in the form of steam. Three configurations are considered: a water tube heat exchanger downstream from the combustion chambers, waterwalls, and a combination of the two. Both substoichiometric and excess air operation are evaluated. Results show the advantages of a configuration with both waterwalls and a convection boiler.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

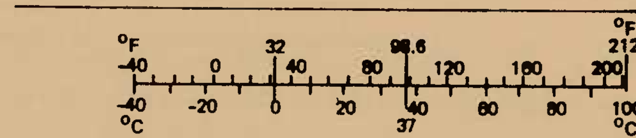
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

INTRODUCTION

This year more than 400 billion pounds of solid waste will be generated in the United States. Most of this waste, possibly as much as 80%, will be disposed of in some type of landfill. Land available for these fills is rapidly being consumed. The price of the land and the distance to an available landfill site are increasing, pushing up the cost of landfill disposal.

Incineration is an alternative to landfill waste disposal. Even poor incineration will reduce the volume of waste by 75%; good incineration reduces waste volume by as much as 95% (Ref 1).

The major drawback to incineration has always been economic. Initial, operating, and maintenance costs were high. It was cheaper to use landfills. Although incinerators have been in use since the late 1800s, to keep costs low they have remained as unsophisticated as practical. They were simply equipment for burning the waste. The combustion was very inefficient. Little concern was shown for air pollution or the inertness of the ash.

There was only moderate interest in recovering the energy of combustion. Again, the reasons were attributable to economics. Boiler tubes continually experienced deposition and corrosion problems (Ref 2); thus, maintenance costs increased still further. Steam generation was sporadic and often unpredictable.

Events in the decade of the 1970s have changed attitudes toward incineration. A growing anxiety for the environment led to legislation governing acceptable levels of gaseous and particulate emissions. The oil crises created an awareness of the limitations of current energy sources. These events, along with the decreasing availability of landfills, have spawned new incinerators; but, of equal significance, they have induced a strong interest in optimizing the design and operation of these new incinerators.

Energy Recovery Incinerators

Energy recovery incineration is a solution to two problems: (1) landfill disposal requirements are decreased by decreasing the volume of the refuse, and (2) fossil fuels are conserved by using the energy of combustion in the solid waste. Figure 1 is a schematic of a typical energy recovery incinerator, the facility at the Naval Air Station (NAS), Jacksonville, Fla.

Heat recovery incinerators were introduced briefly in the United States around 1900; energy recovery was initiated in Europe about this same time and practiced modestly in the last 30 years. Nearly all of the U.S. incinerators and most of the European devices, however, were constructed by simply adding a downstream heat exchanger to recover some of the energy remaining in the exhaust (i.e., adding to an existing, and usually inefficient, refractory incinerator).

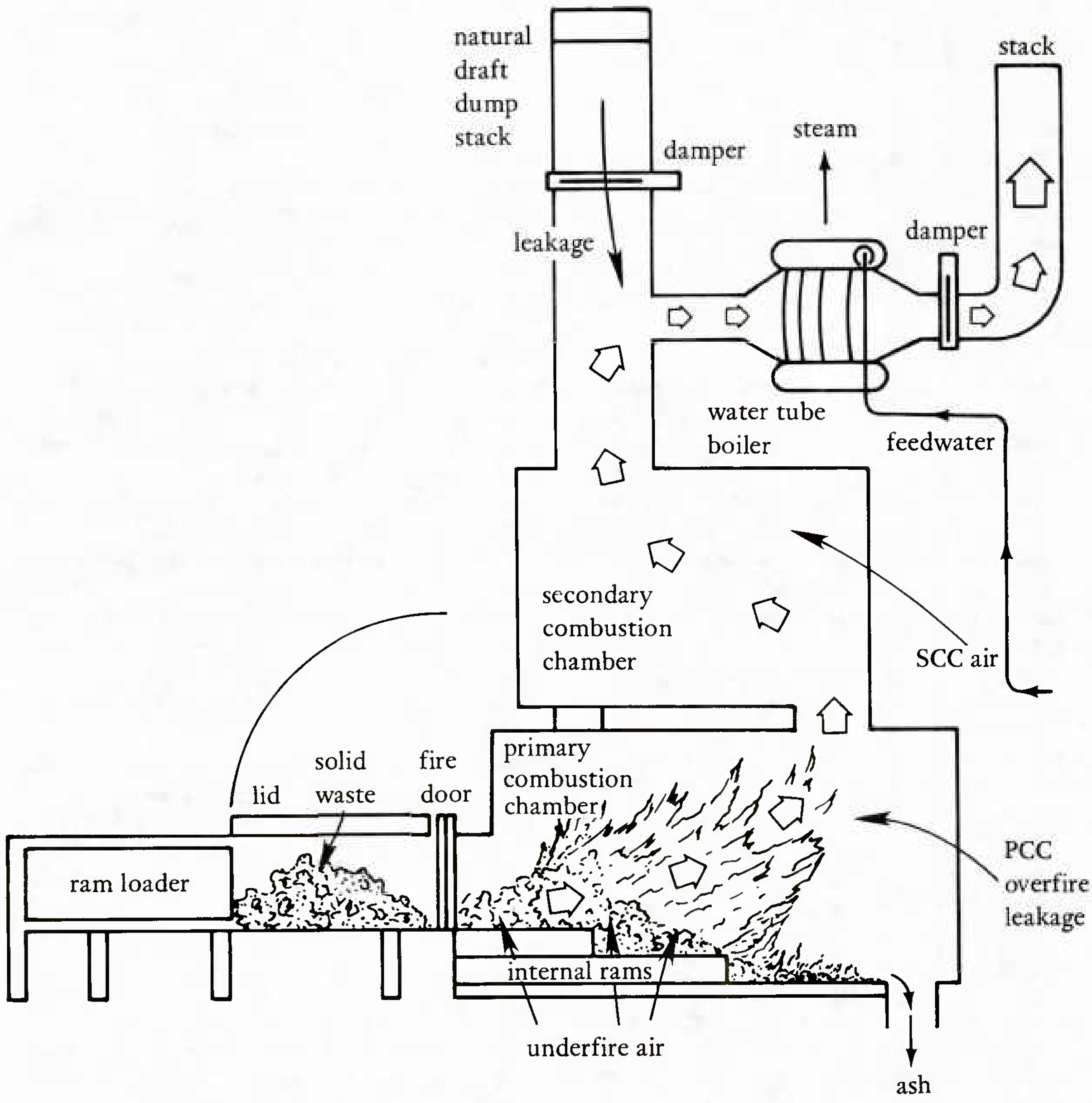


Figure 1. Schematic of energy recovery incinerators at Naval Air Station, Jacksonville (Ref 4).

Optimizing the design includes examining other configurations. Combustion chamber waterwalls,* similar to the configurations common in coal burning facilities, are an example. Refinements, such as slagging incinerators and fluidized beds, could be investigated.

Extent of This Work

This work is a theoretical thermal evaluation of different energy recovery incinerators by parametric examination and, to the extent possible, by direct comparison. Admittedly, a one-to-one comparison is not always valid. Parameters can hold a different level of importance in different configurations. The evaluation criteria consist of thermal efficiency, temperatures, and stability of operation. Stability means the sensitivity of thermal efficiency (e.g., steam generation) or temperatures (e.g., flame temperature) to changes in operating conditions.

The plan-of-attack is to model the incinerator mathematically, using a computer program (called HRI (Ref 3)) to solve the governing equations, and use this model to make the evaluations.

The energy recovery incinerators studied are the smaller, about 24-tpd, devices.** Energy recovery is in the form of steam. Three configurations are considered: a water tube heat exchanger downstream from the combustion chambers, waterwalls, and a combination of the two. Both substoichiometric and excess air operation are evaluated. Underfire, overfire, or secondary combustion airflow is usually used as the independent variable.

The dual combustion chamber energy recovery incinerators at NAS Jacksonville have been parametrically examined in detail (Ref 4). This facility is used to represent the downstream, water tube heat exchanger configuration. The other two configurations are hypothetical, although many of the dimensions and operating conditions are assumed to be identical to the Jacksonville incinerators to compare facilities of roughly the same capacity. The three energy recovery incinerators are described in Appendix A.

This is the final report on the modeling of energy recovery incinerators. Combined with References 3 and 4, it provides both the guidelines and the tool for conducting the thermal analyses of these devices.

COMMENTS ON SOME PARAMETERS

To provide a foundation for the energy recovery incinerator evaluation, a brief discussion of each configuration and a discussion of the combustion airflows are presented. Both thermal considerations, which will be amplified later, and mechanical considerations, which will not, are included.

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*A waterwall incinerator was installed by the Navy at the Norfolk shipyard in 1967. This was a 180-tpd device generating about 50,000 lb/hr of 275-psig steam using 50% excess air.

**Most of the results are equally applicable to the larger municipal incinerators.

Waterwall Boilers

Waterwalls are a type of boiler in which the tubes form the walls of the furnace. Normally, they are in close proximity to the hearth, and thermal radiation from the flame plays a role of importance equal to convection from the combustion products in providing the heat flux for the generation of steam.

The major operational advantage of waterwall incinerators is the stability they give to flame temperature, stability with respect to changes in type of waste and feed rate as well as changes in combustion and leakage airflows.

Conversely, the major disadvantage of waterwall incinerators is the instability of the steam generation. This is attributable to the sensitivity that radiation from the flame* has to changes in chemical energy release (e.g., to changes in the composition of the fuel, moisture content, or feed rate). A second disadvantage is a vulnerability to the corrosive effects of products of pyrolysis and products of incomplete combustion. For example, carbon monoxide, hydrogen chloride, and hydrogen sulfide are known to attack metal surfaces (Ref 2,5,6,7). The problem becomes particularly severe for starved air operation. Finally, because of their location, waterwalls are vulnerable to the erosive effects of the solid particulate carried along with the combustion products.

Convection Boilers

Convection (usually water tube) boilers are heat exchangers in which the tubes are placed in the path of the combustion gases, and steam is generated from the energy transferred by convection. This is the configuration shown schematically in Figure 1.

With a convection boiler, the major advantages and disadvantages are reversed. Energy recovery efficiency is stable, but the flame temperature is very sensitive to changes in incinerator operating conditions. A second disadvantage concerns the refractory. Convection boiler incinerators inherently require more refractory, and this material tends to fail when subjected to the continual heating up and cooling down common with many incinerators (Ref 5).

Waterwalls Plus Convection Boiler

The above characteristics suggest that combining waterwalls and a convection boiler might prove beneficial.

Starved Air Operation

Starved** air operation refers to the condition where air supplied to the fuel in the first combustion zone (the flame or perhaps the flame and primary combustion chamber) is not sufficient to support stoichiometric combustion.

---

*Recall that thermal radiation is proportional to the fourth power of the temperatures.

**The term substoichiometric is sometimes applied here.

Most types of waste (e.g., paper and wood) are distilled when subjected to heat (Ref 4). This distillation process, called pyrolysis, is an irreversible degradation of the solid to form various volatile gases, tars, and a carbonaceous solid residue. Tar contains substances that are volatilizable at higher temperatures (Ref 8).

The volatile matter is emitted volumetrically from the interior of the solid and represents the primary combustibles. With most types of waste, the volatiles comprise about 80% of the total mass. Once the volatiles are released, the carbon residue is itself combustible.

The heat of pyrolysis may be endothermic or exothermic depending upon the type of solid and local temperature. For most types of waste it is close to being thermally neutral (Ref 8).

Thus, under starved air conditions, the gases in the combustion zone are composed partly of the products of pyrolysis, partly of water vapor and carbon dioxide, partly of nitrogen and, perhaps, partly of products of incomplete combustion.

The primary advantage of substoichiometric operation is environmental. When air velocities through the burning waste are low, carryover of the solid particulate is low. Starved air systems also have higher energy recovery efficiencies. Flames have to be kept cool to prevent, for example, glass and aluminum from melting. Typically, the flame temperature is restricted to about 1,800°F, with cooling accomplished either by starving the air to limit the energy release or by diluting the products of combustion with excess air. Most boilers are able to reliably operate with gas temperatures greater than 2,000°F.* When excess air is supplied to the flame, combustion is completed and boiler/ waterwall temperatures are limited to 1,800°F. If the underfire air is substoichiometric, however, combustion is continued overfire and/or in a second combustion chamber, and higher boiler gas temperatures and, thus, higher boiler heat transfer rates can be achieved.

There are disadvantages with starved air systems. Control of the incinerator is difficult. Starved air systems must also be capable of operating in an excess air mode; changes in fuel characteristics often force them into such a mode. The correct response to a high substoichiometric flame temperature is opposite to the correct response to a high excess air flame temperature. The current operating point must be identified, and this requires more than a simple temperature measurement. Several temperatures or, perhaps, gas composition must be determined. Controls capable of making this distinction are complex and expensive. A related disadvantage is the extreme sensitivity of starved air incinerators to changes in operating conditions. Another disadvantage is the corrosive effect of the products of incomplete combustion on incinerator components.

<u>Combustion Air Inlet Locations</u> (Ref 1)

The chief function of underfire air is to achieve burnout of the waste; underfire air must be sufficient to sustain the combustion level necessary to evaporate the moisture in the waste, pyrolyze the waste, and then burn the char. In addition, the underfire airflow rate must be

*There are several limiting factors: stresses, keeping particulates in a solid state to prevent "freezing" on tube surfaces (Ref 6), etc.

high enough to protect the grate, low enough to minimize particulate carryover, and high/low enough to control the flame temperature and thus prevent slagging and clinkering.

For excess air operation, the primary function of overfire air is to promote the turbulence necessary to mix the oxygen and pyrolysis products. This insures complete combustion and a homogeneous combustion chamber environment, free of hot spots and free of the corrosive effects caused by some of the products of incomplete combustion. For starved air operation, the primary function of overfire air is to control the temperature of the furnace overfire environment, maximizing heat transfer to the waterwalls (when applicable) within the temperature limitations imposed on the tubes and the flame* zone. In some systems, overfire air is also used to cool the refractory.

Combustion air is supplied to the secondary combustion chamber to complete combustion of the pyrolysis products, when necessary, and to control the temperature of the combustion gases entering the convection boiler. A few incinerators have secondary combustion chamber waterwalls.

SOLID WASTE COMBUSTION CHEMISTRY (Ref 8)

The combustion of waste involves several individual processes in both series and parallel. In broad terms, waste combustion combines reactions of the solid (pyrolysis and the combustion of the carbon residue) with reactions involving the gases (cracking of the tars and, finally, combustion of the volatiles).

The pyrolysis of waste was discussed previously. This thermal decomposition is dominated by the depolymerization and condensation reactions of cellulose but with contributions from polyethylene and other man-made and natural polymers. During the decomposition, compounds are produced that are less stable than the starting material. There is competition between escaping from the solid (volatilization) or undergoing further reactions (condensation, ultimately leading to the formation of char). The overall result is the creation of scores of products whose relative concentrations are controlled by physical parameters such as heating rates and temperatures. The time frame associated with pyrolysis is, of course, heat transfer controlled, but in most incinerators it is probably on the order of seconds.

Char yields of about 10% by weight are typical. Combustion of the char is slower than combustion of the volatiles by several orders of magnitude and is much slower than most pyrolysis reactions. Regardless, ignition of the volatiles usually produces such a rapid temperature increase that the consumption of the char, albeit lagging, is accomplished very rapidly. The overall combustion reactions are (Ref 9, 10):

$$2C + O_2 \rightarrow 2CO$$

$$2CO + O_2 \rightarrow 2CO_2$$

*As will be shown later, radiation from the overfire combustion gases back to the flame is not insignificant.

At high temperatures, there is experimental evidence suggesting that the reduction of carbon dioxide by the carbon at the solid surface is also a significant mechanism (Ref 10),

$$CO_2 + C \rightarrow 2CO$$

Temperatures of 1,800°F and residence times in minutes are sufficient to crack most tars. Both are typical with incinerators.

When additional oxygen is present (in excess of that required to burn the char) or added overfire or into a secondary chamber, some or all of the volatiles are consumed. The chemical reactions are very rapid. Diffusion flames are expected, controlled by heat and mass transfer. Under such rapid burning conditions, combustion occurs by layers, and the unburnt gases have about the same composition as the reactants (with additional carbon dioxide and water vapor). This is an "all or nothing" process. Ignition occurs, temperatures rise rapidly, and all local carbon and hydrogen is converted to carbon dioxide and water vapor. If the incinerator is starved, the unburnt volatiles are simply heated up.

MATHEMATICAL MODEL

A diffusion flame is hypothesized.

Although it would be beneficial to identify the composition of the gases at various locations throughout the incinerator, the problems are overwhelming. There are hundreds of pyrolysis and combustion products whose relative concentrations are influenced by and, simultaneously, influence the operation of the incinerator. Time as well as steady state conditions, such as temperature, become important.

No attempt will be made to identify the gases. For purposes of specific heat and emissivity calculations, the waste is assumed to be burned, within the limits of the available oxygen, completely to carbon dioxide and water vapor. Products of pyrolysis not consumed will be assumed cracked to hydrogen, carbon monoxide, and carbon dioxide (Ref 8).

Thus, the waste* combustion is simulated by the reaction

$$C_{n_1}H_{n_2}O_{n_3}N_{n_4} + n_5H_2O + n_6O_2 + 3.76\ n_6N_2 \rightarrow$$

$$n_7CO_2 + (n_5 + n_8)\ H_2O + n_9CO + n_{10}O_2$$

$$+ (0.5\ n_4 + 3.76\ n_6)\ N_2 + n_{11}H_2 + n_{12}C \qquad (1)$$

*The composition of the waste assumed for these analyses is included as Appendix B.

In addition, it is assumed that:

1. Steady state exists.
2. Kinetic and potential energy changes are negligible.
3. The reactions go to completion regardless of the temperature.
4. The products of combustion are perfectly mixed.
5. All temperature gradients are normal to the incinerator walls; individual components of the incinerator can be represented one dimensionally.
6. The incinerator is operating at atmospheric pressure.
7. All gases are ideal.
8. The flame does not touch the wall. (The flame is defined as the region influenced by underfire air.)
9. There is always enough energy released to pyrolyze the waste.
10. Both the flame and the inside of the combustion chambers act as black bodies. The products of pyrolysis/combustion are gray.

The molar coefficients n_1 through n_5 are obtained from ultimate and proximate analysis of the waste; n_6 is from the air supplied for combustion. Equation 1 is balanced by applying conservation of species and allocating available oxygen linearly.

Heat absorbed in breaking down the waste, primarily a heat of pyrolysis, is determined by balancing Equation 1 for stoichiometric air, then subtracting the heats of formation of the combustion products from the heating value of the waste. Once the heat of pyrolysis is known, heat released during combustion with less than stoichiometric air is back-calculated in an analogous manner.

By applying conservation of energy to the flame, primary combustion chamber (PCC), secondary combustion chamber (SCC), and boiler, in sequence, temperatures throughout the incinerator and, finally, steam generation are determined.

The details of the mathematical simulation, including an estimate of accuracy, are given in Appendix C.

PERFORMANCE CRITERIA

The efficiencies of both the boiler alone and the overall heat recovery incinerator are defined using the heat loss method (Ref 11),

$$\eta \equiv 1 - \frac{\Sigma \text{ LOSSES}}{\Sigma \text{ INPUT}} \qquad (2)$$

For the boiler:

Σ LOSSES = sensible heat in stack gases + steam lost to blowdown

Σ INPUT = sensible heat in products of combustion entering boiler + sensible heat of feed water

For the overall energy recovery incinerator:

Σ LOSSES = heat lost vaporizing moisture with waste + heat lost vaporizing moisture generated by burning hydrogen in waste + carbon carried out as ash + sensible heat of ash + heat transfer through walls of PCC and SCC + products of incomplete combustion in stack gases + sensible heat in stack gases + steam lost to blowdown

Σ INPUT = chemical energy in waste and oil + sensible energy in waste, oil, air, and feed water + external power requirements

This definition of efficiency is preferable because it isolates the individual components of the energy recovery incinerator, simplifying identification of significant parameters. Individual terms in the summations are mathematically described in Appendix D.

PARAMETRIC EXAMINATION

Different parameters affecting the operation of energy recovery incinerators are examined. These parameters include controlled inputs, such as combustion airflow and waste feed; uncontrolled inputs, such as leakage air; physical characteristics, such as heat transfer; and, finally, design characteristics, such as the type and size of the heat exchangers.

Combustion Air

Both underfire and overfire air can be controlled as the means of controlling the operation of the incinerator. Overfire combustion does have an effect on flame temperature, changing thermal radiation between the PCC combustion products and the flame. However, with low flame temperatures, i.e., with waterwalls, this effect is limited. Underfire air usually makes a better instrument for incinerator control. Figures 2 through 5 show incinerator temperatures and efficiencies plotted as a function of underfire or overfire air.

Figure 6 shows the effects of secondary combustion chamber airflow on the performance of energy recovery incinerators. There is a strong dependency between SCC temperature and SCC airflow; nevertheless, the overall efficiency of the incinerator is not a strong function of SCC temperature. Increasing SCC airflow decreases the combustion chamber temperature and, subsequently, the temperature gradient across the boiler tubes, but this effect is partially compensated for by increased heat transfer characteristics induced by the increase in the velocity of the gases flowing over the water tubes,

$$h_{CONV} \propto N_{Re}^{n}$$

where

h_{CONV} = convection heat transfer coefficient

N_{Re} = Reynolds number $\propto$ velocity

n = constant

Efficiency advantages of starved air incinerators are apparent when Figure 6 is examined closely. About 45% of stoichiometric air is provided to the PCC. By adding air to the SCC, combustion of the remaining pyrolysis products is completed, and gas temperatures are raised to any limit tolerated by the convection boiler. For example, if the boiler is designed for 2,000°F combustion gases and the flame temperature is limited to 1,800, the extra 200°F is worth an energy recovery efficiency increase of 3 and 7% with and without waterwalls, respectively. (Move from 1,800 to 2,000°F along the SCC temperature curves on Figure 6 and note the corresponding increase in overall efficiency.)

Combustion Air Temperature

Sensible energy remaining in the stack gases is the largest incinerator performance loss. One method used to increase the efficiency of these devices is to use some of this energy to preheat the combustion air, a technique common with coal boilers.

The initial temperature of the combustion airflow is used as the independent variable in Figure 7. On these graphs, the total airflow is held constant. Another way of showing the advantages of preheating might be to hold the flame temperature constant and change the combustion airflow.

When operating below flame and/or boiler temperature limits, air preheating can be used to raise these temperatures and, therefore, steam generation as shown in Figure 7 (all other input remaining constant). Alternatively, when already operating at maximum allowed temperatures, airflows can be increased, increasing the heat transfer rate between the combustion products and the waterwalls and/or tubes, thus increasing steam generation rates. (Increasing airflows is, of course, not a valid modification when the incinerator is starved.) Assuming a stack gas temperature of 500°F and using it to preheat the air to 200°F, the efficiency of the energy recovery incinerator might be increased by 4 or 5%.

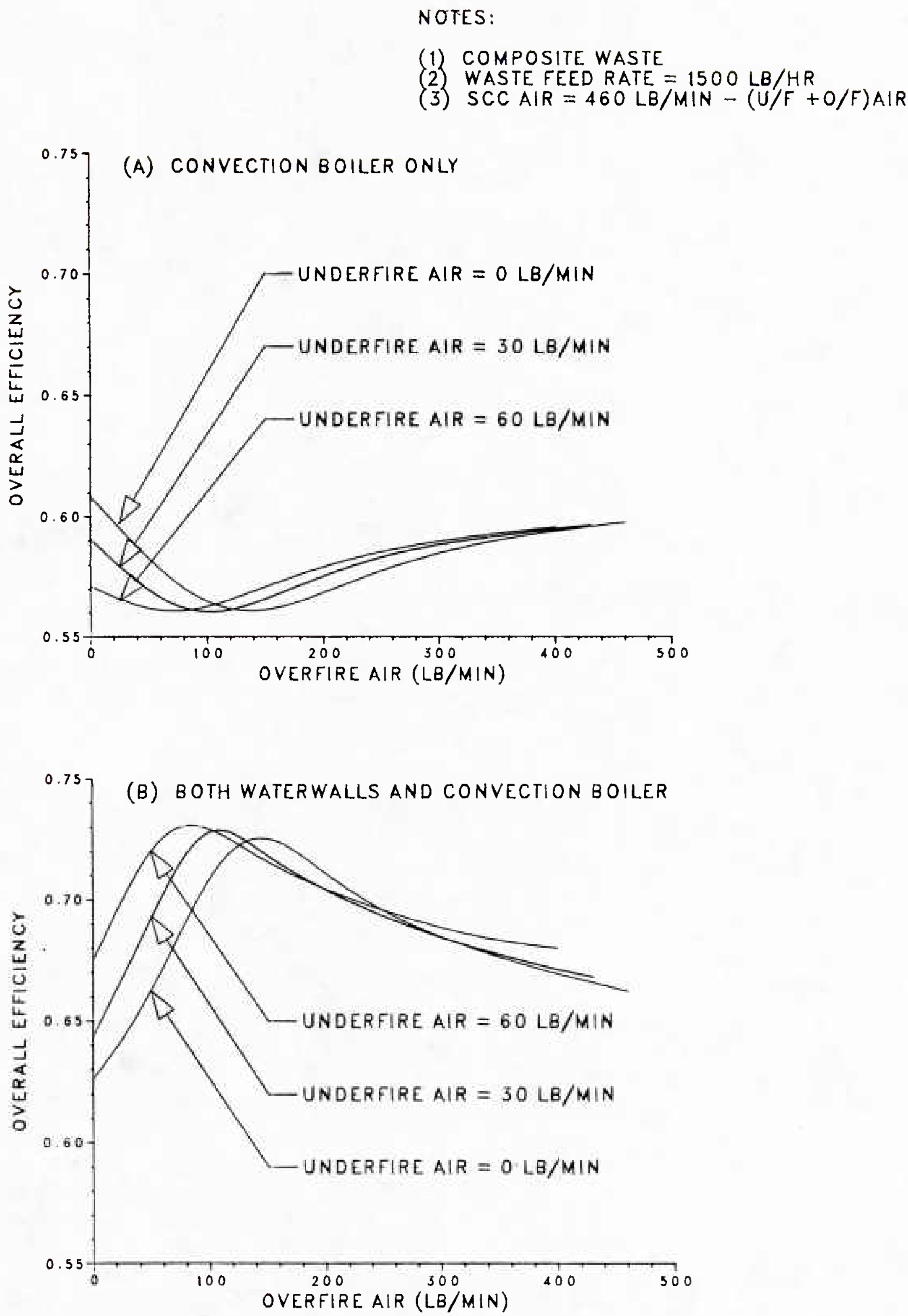


Figure 2. Effect of overfire air on the efficiency of energy recovery incinerators.

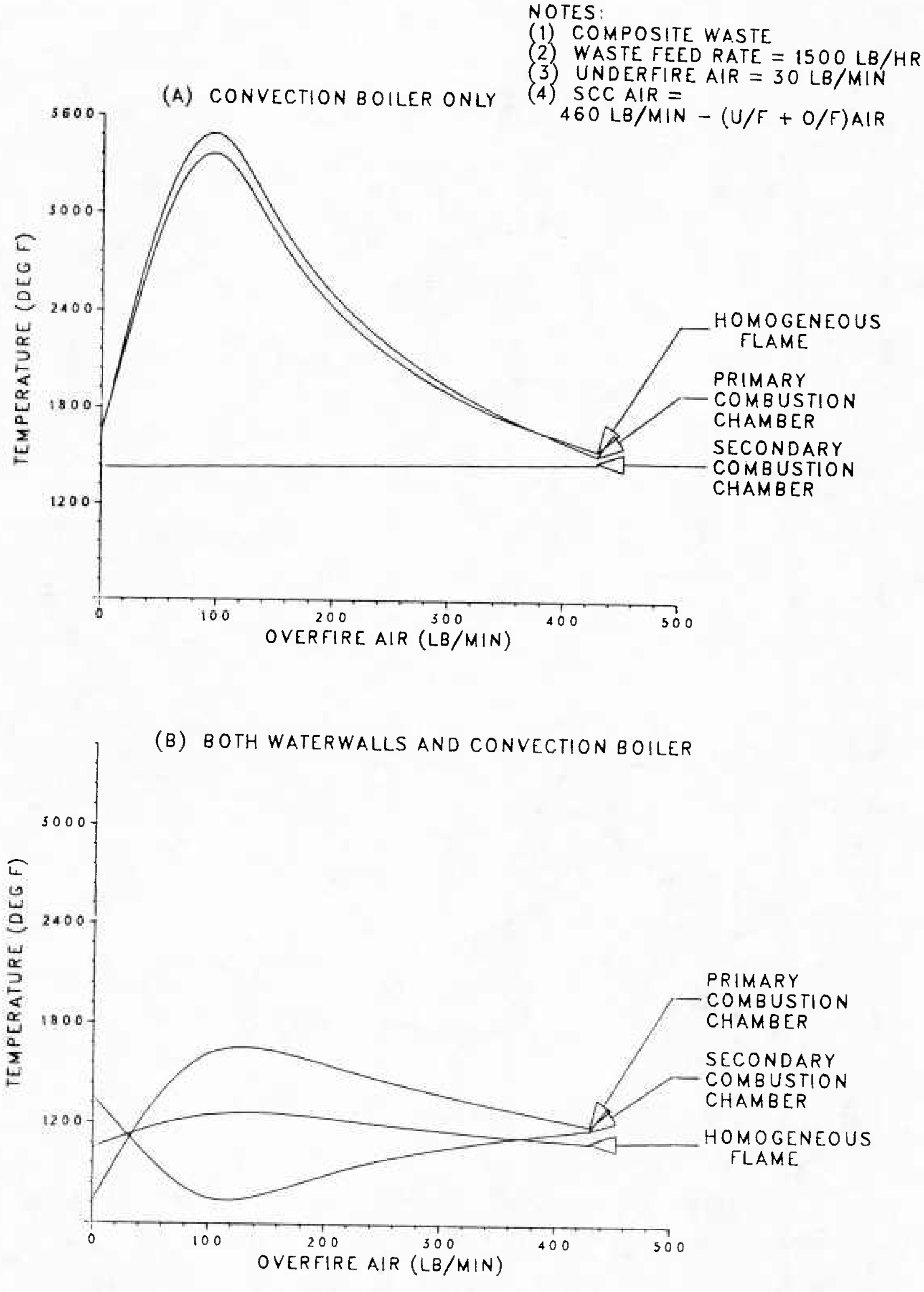


Figure 3. Effect of overfire air on temperature profiles through different energy recovery incinerators.

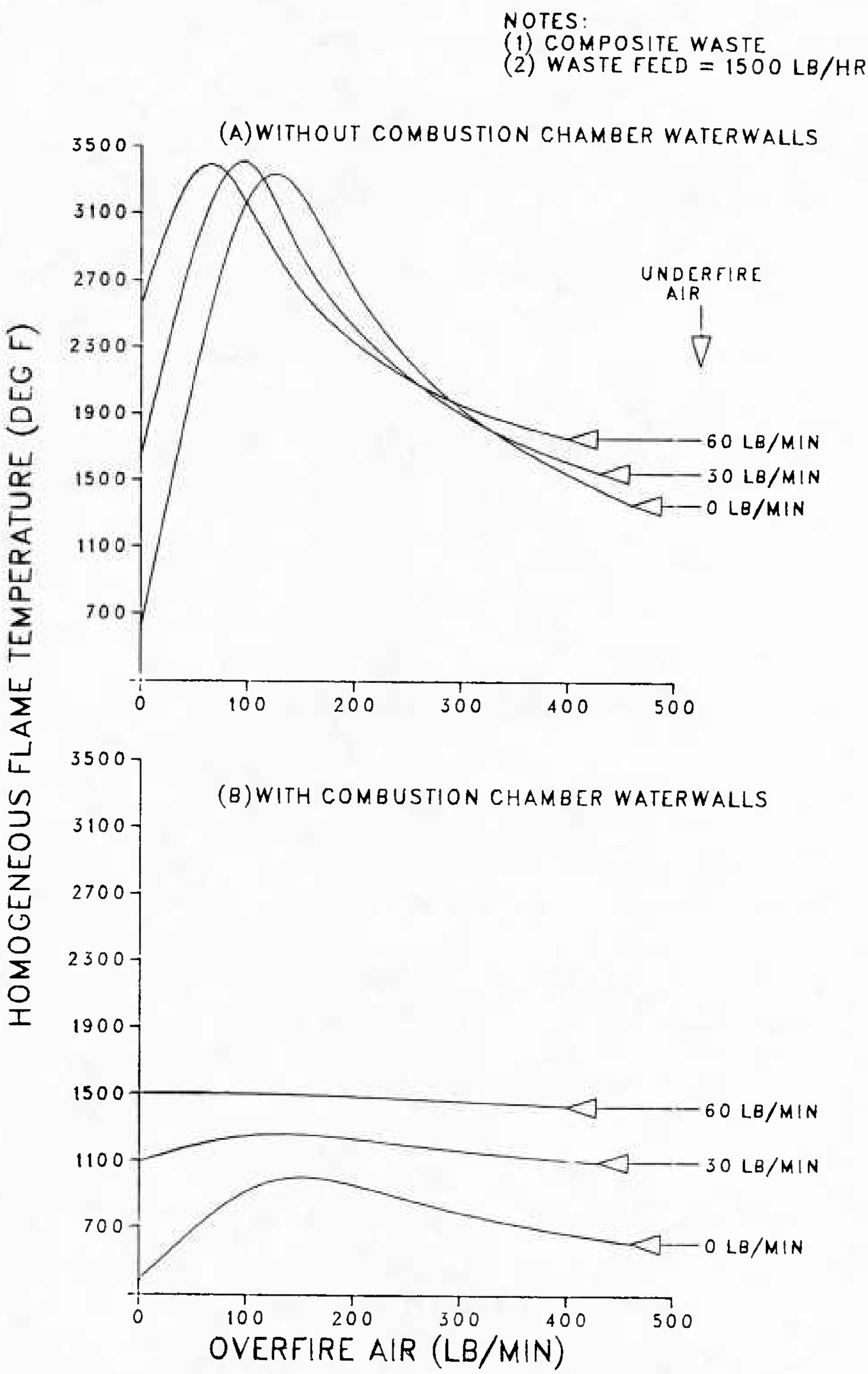


Figure 4. Effect of overfire air on the flame temperature of an energy recovery incinerator.

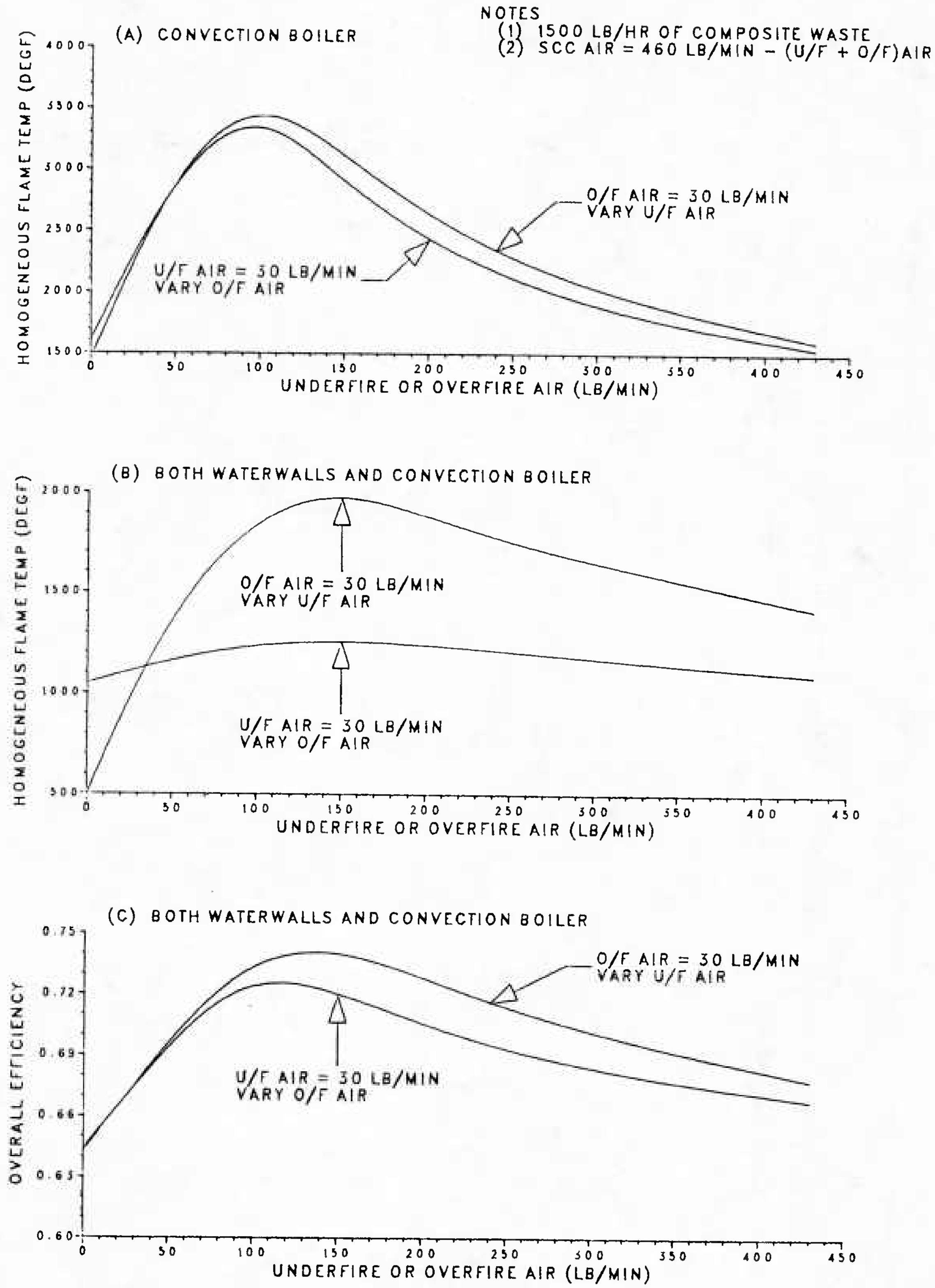


Figure 5. Comparison of underfire and overfire air as the means of incinerator control.

NOTES:

(1) 1500 LB/HR OF COMPOSITE WASTE
(2) UNDERFIRE AIR = 30 LB/MIN
(3) OVERFIRE AIR = 30 LB/MIN
(4) STOICHIOMETRIC AIR = 136 LB/MIN

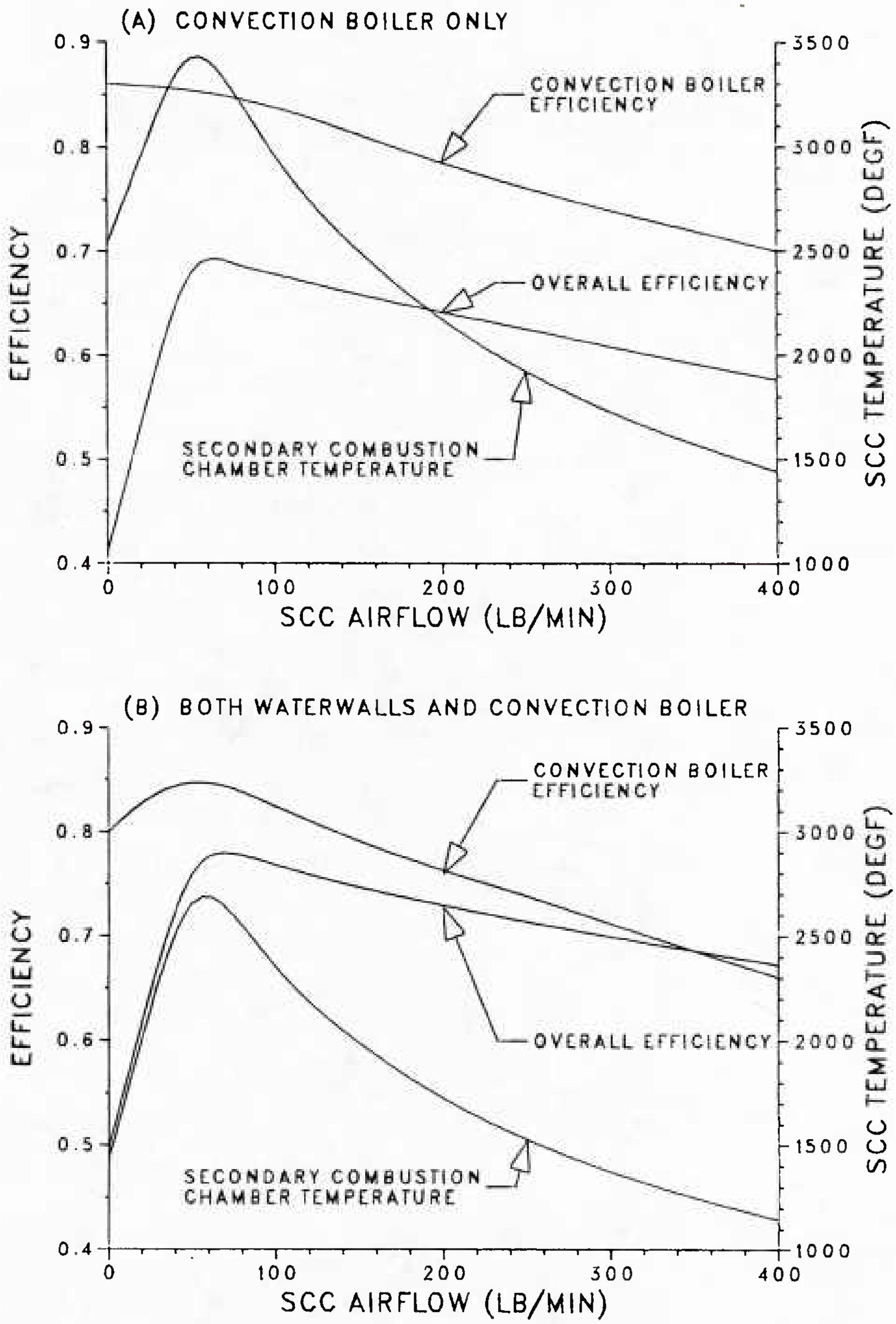


Figure 6. Effect of secondary combustion chamber airflow on the performance of energy recovery incinerators.

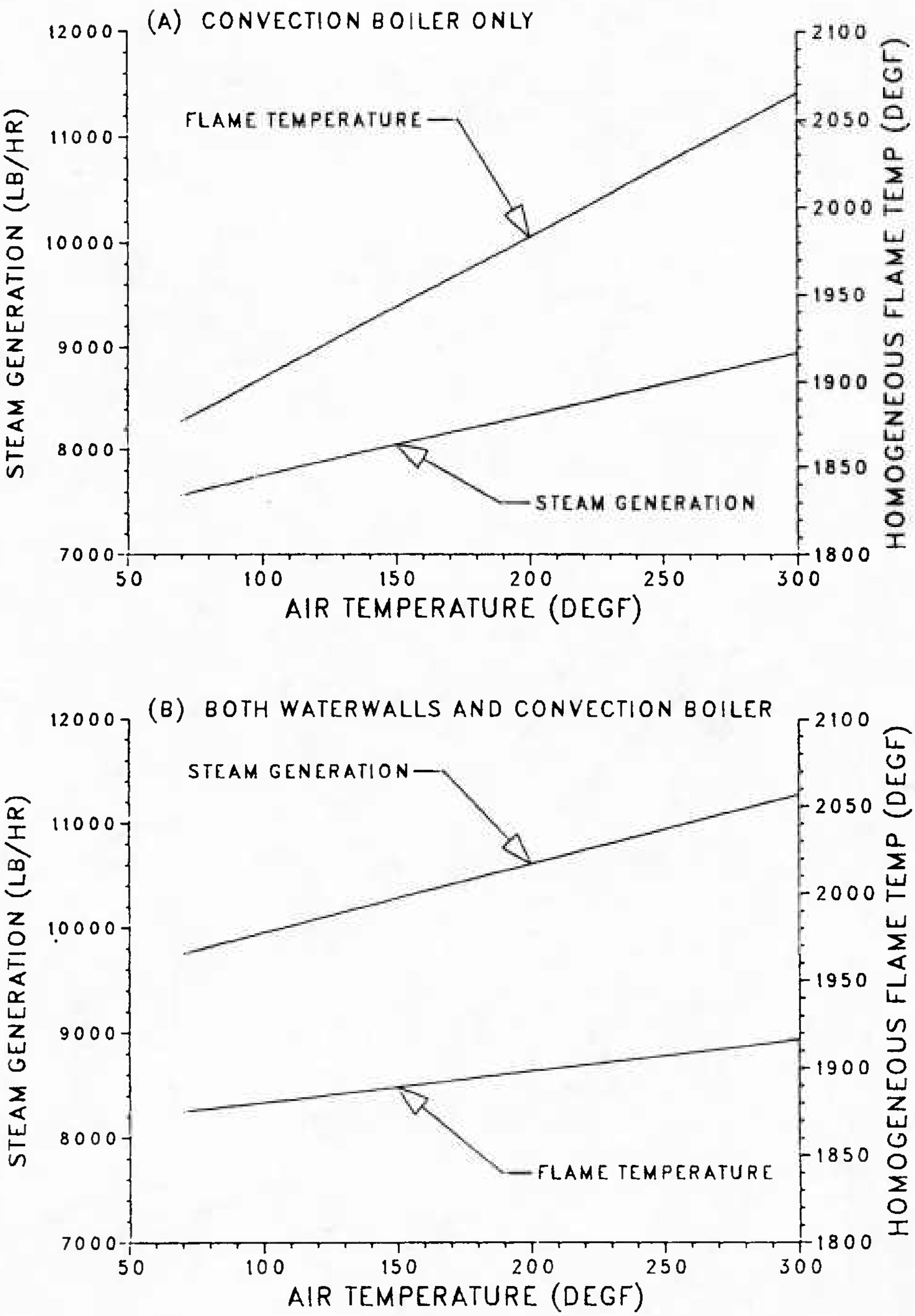


Figure 7. Effect of initial temperature of the combustion air on incinerator operation.

Air Leakage

Leakage down the dump stack has little effect on the performance of energy recovery incinerators. This is apparent in Figure 8. The explanation is analogous to the explanation given in the Combustion Air section: the decrease in gas temperatures induced by the addition of the cooler ambient air is partially compensated for by the increase in convection coefficient induced by the increase in mass flow rate (Reynolds number).

Air leakage into the combustion chamber is a more severe problem. Leakage here is tantamount to changing the combustion airflow. The effects are illustrated in Figure 9. Effects of leakage are greater when the incinerator is starved. In the example shown in Figure 9, a 40-lb/hr air leak causes up to a 900°F increase in the flame temperature. When waterwalls are used, air leakage, particularly overfire leakage, is less of a threat.

Type of Waste

Figures 10 and 11 illustrate different operating conditions expected with different incinerator configurations burning different types of waste. These curves can only be considered typical (e.g., moisture in the waste varies considerably even in the same type of waste). These curves do, however, illustrate the problems inherent in the control of energy recovery waste incinerators. For example, the starved air combustion of plastics requires the same air as the excess air combustion of the cellulose-type wastes.

The same trends exist for operational fluctuations in type of waste as in most other parameters: waterwall incinerators tend to have a stable flame, while the energy recovery efficiency of convection boiler devices is stable.

Waste Feed Rate

The same observations on control problems and stability trends are pertinent if the parameter is the waste feed rate. Figures 12 and 13 illustrate this. Although such radical changes in feed rates are unlikely if the incinerator is even moderately well-operated, fluctuations in other factors, such as density and moisture content, are tantamount to changes in feed rate.

Moisture Content

The major loss attributable to moisture is not the heat lost vaporizing the water but the decrease in the actual amount of fuel burned. The heat of vaporization, about 970 Btu/lb, although significant, is small compared with the heating value of the waste, typically about 8,500 Btu/lb. In Figures 14 and 15, a 30% moisture content would decrease energy recovery efficiencies by only about 5% while steam generation falls off by nearly 35%, the energy lost vaporizing the waste plus the decrease in the dry weight of the waste burned.

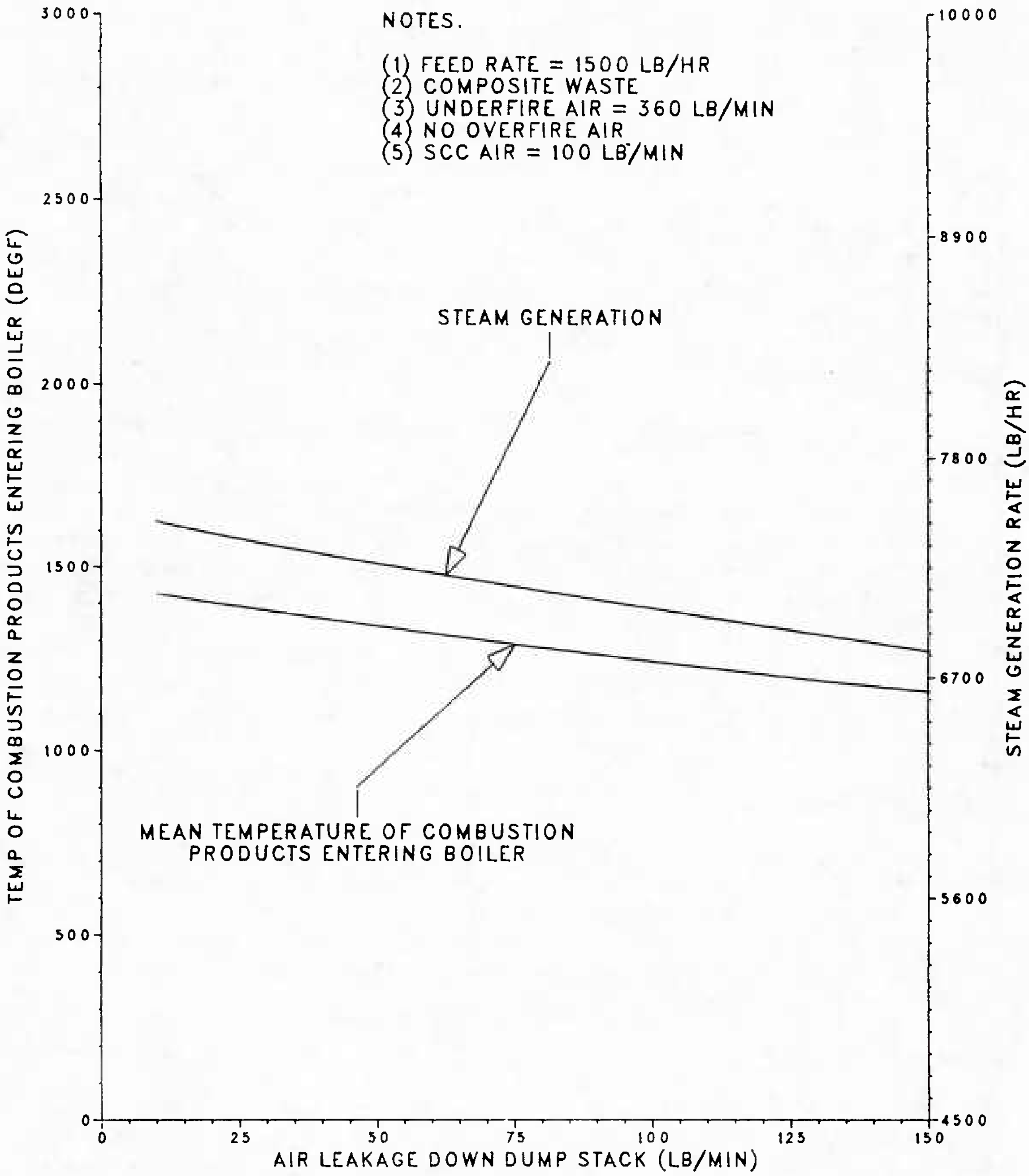


Figure 8. Effect of leakage down the dump stack on steam generated by convection boiler energy recovery incinerator.

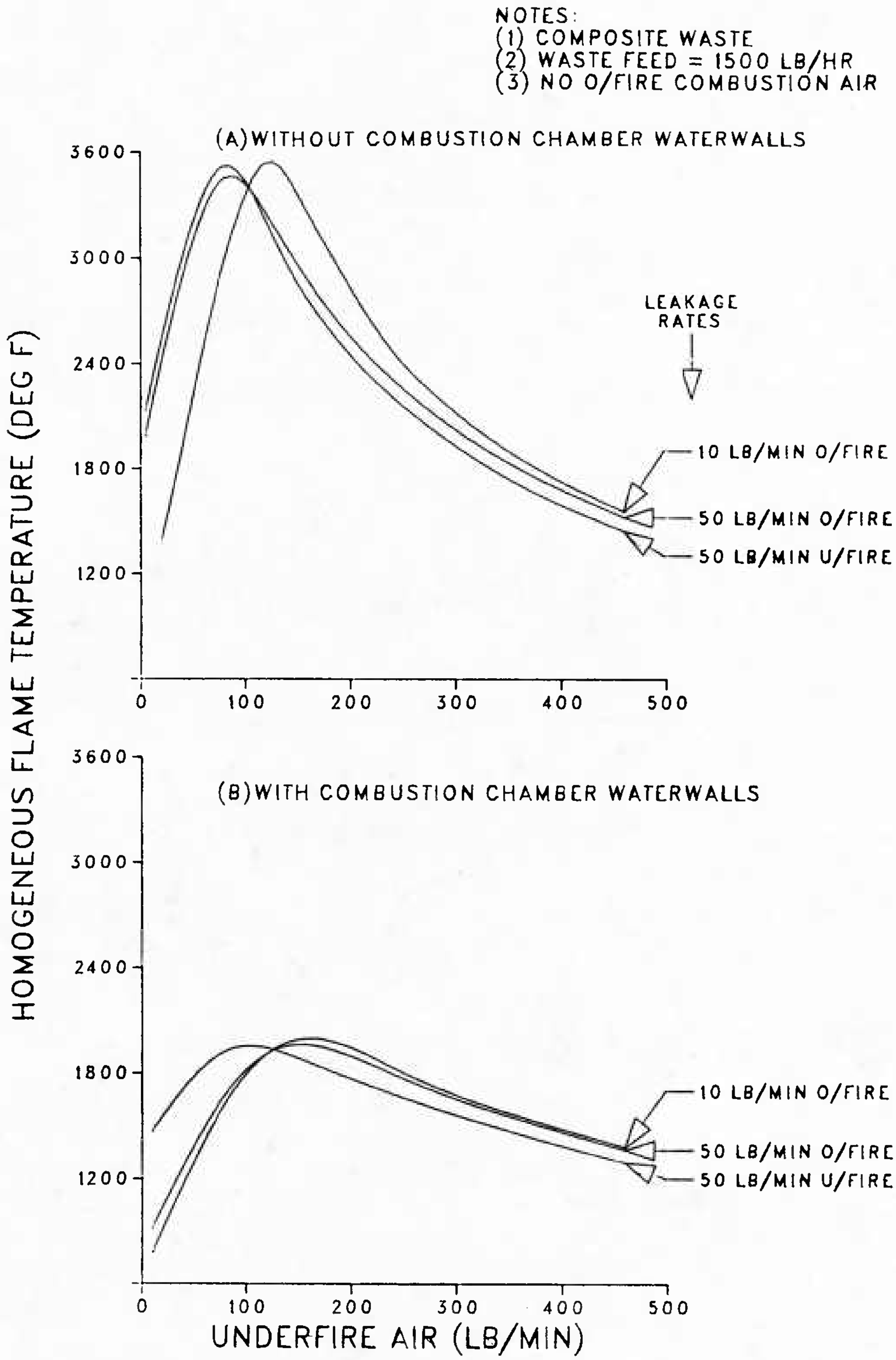


Figure 9. Effect of air leakage on the flame temperature of an energy recovery incinerator.

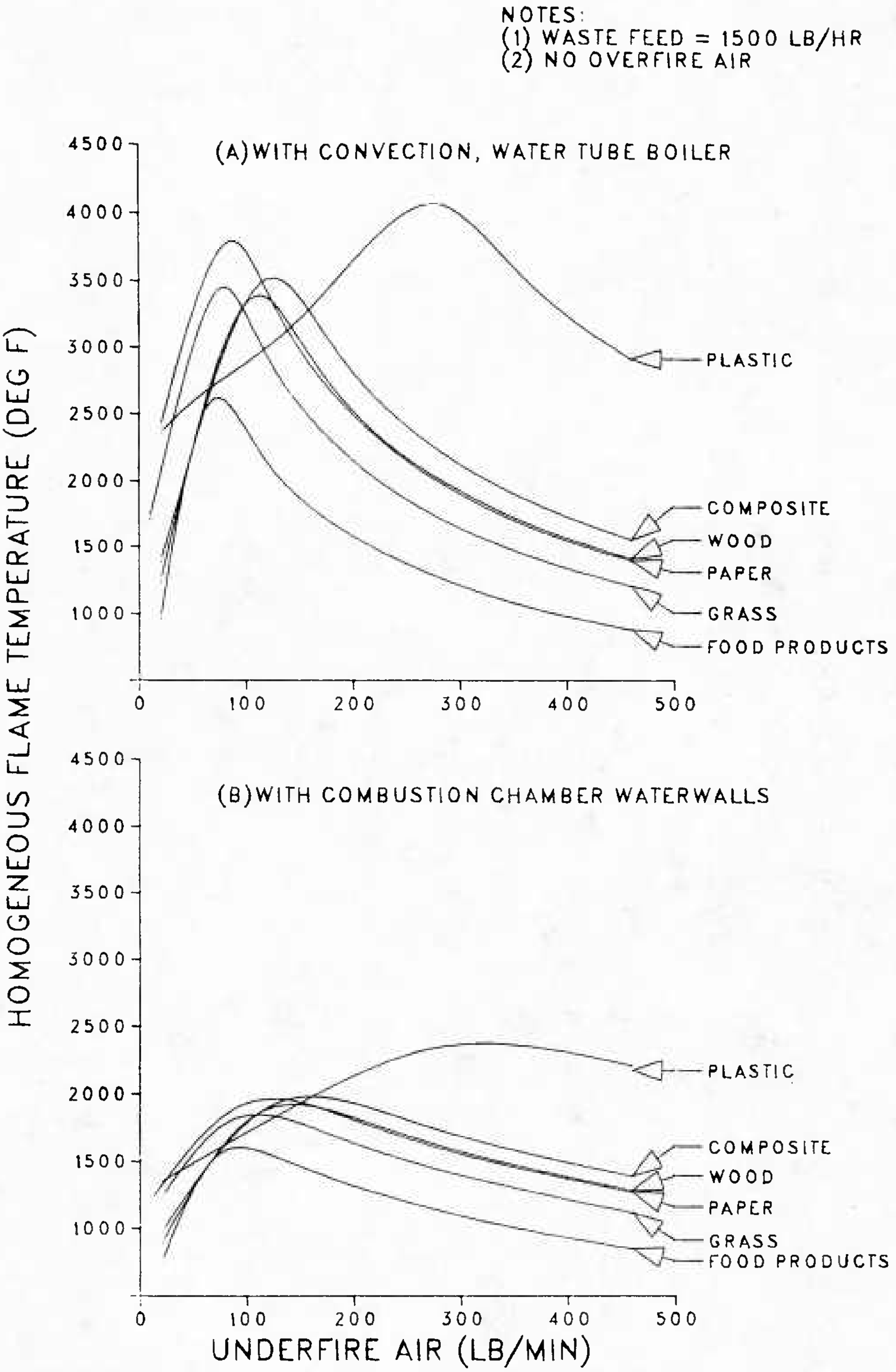


Figure 10. Effect of type of waste on the flame temperature of an energy recovery incinerator.

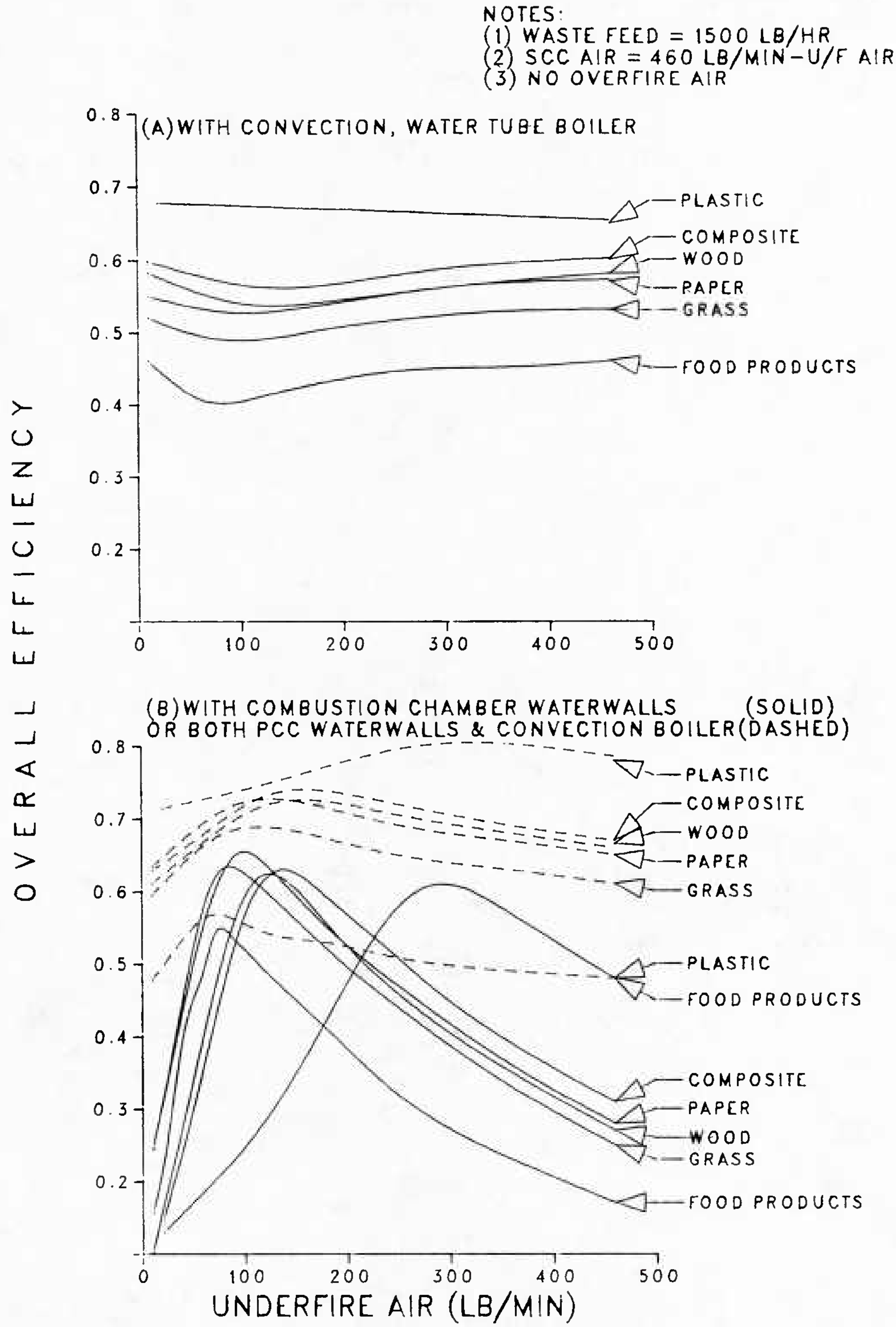


Figure 11. Effect of type of waste on the overall thermal efficiency of an energy recovery incinerator.

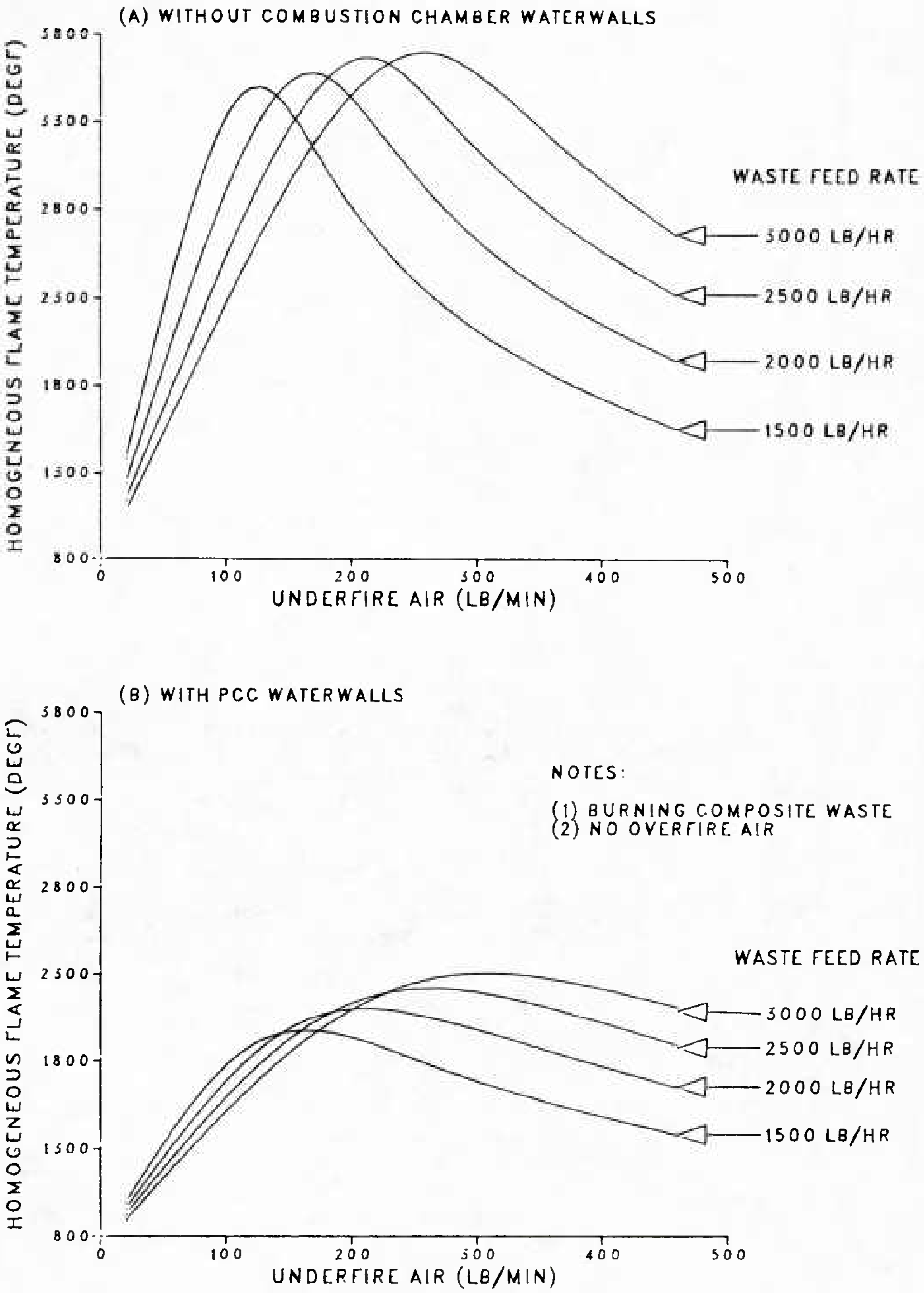


Figure 12. Effect of waste feed rate on the flame temperature of an incinerator.

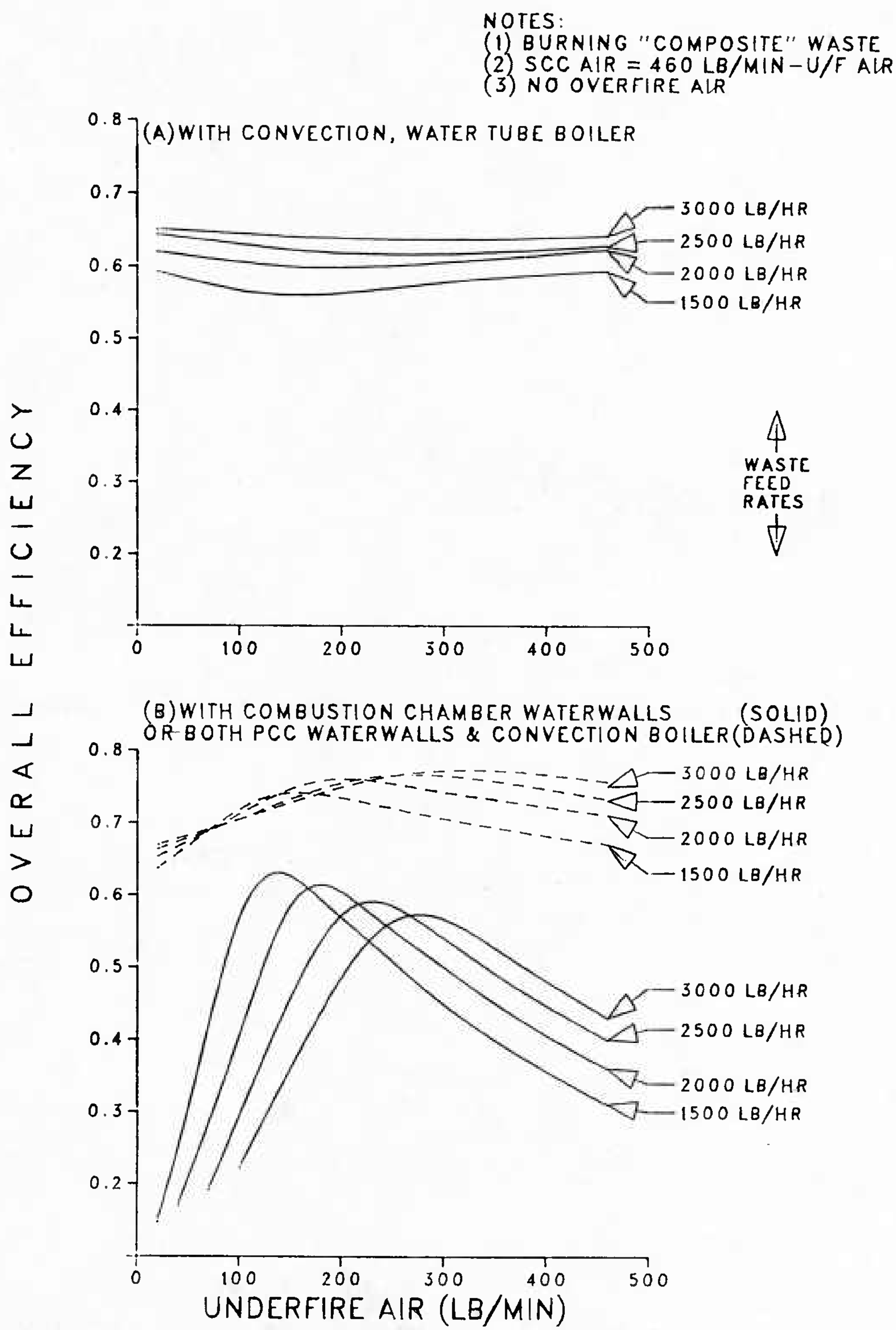
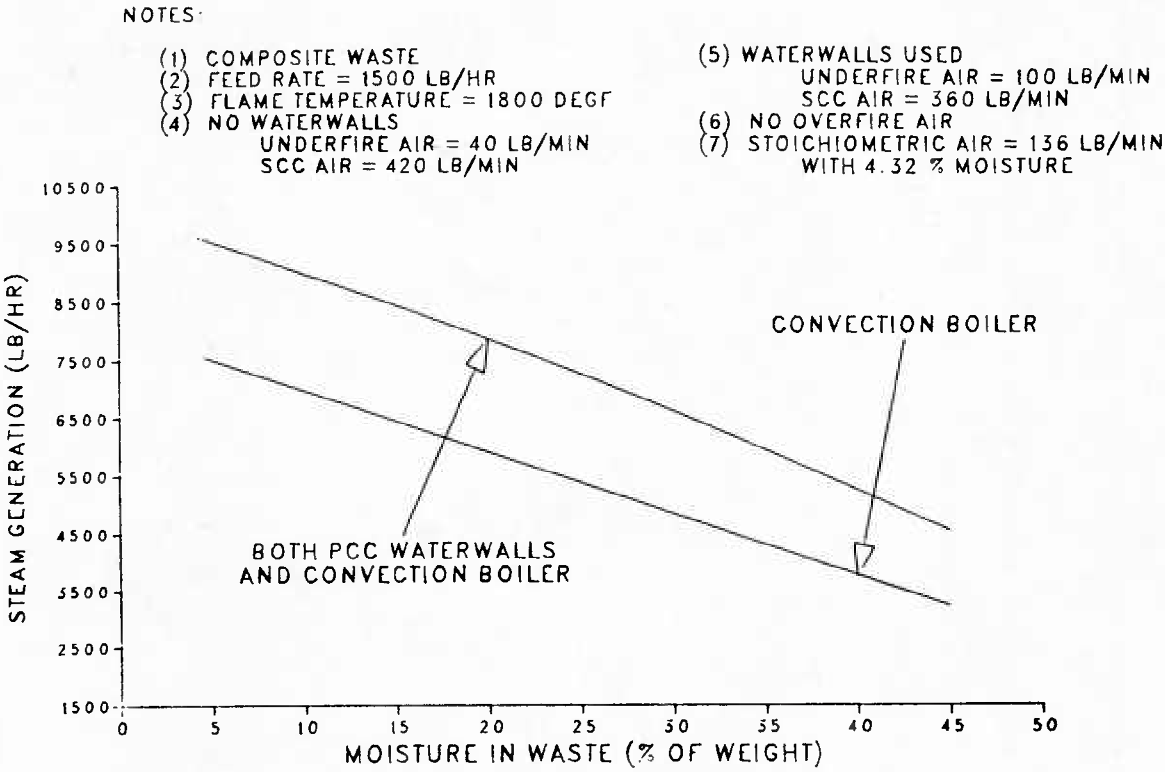
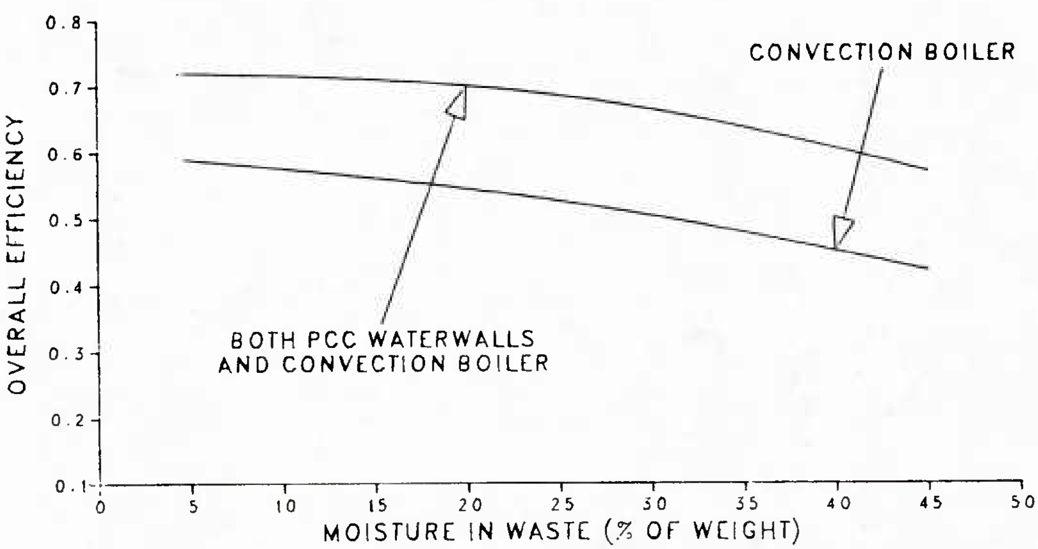


Figure 13. Effect of waste feed rate on the overall thermal efficiency of an incinerator.

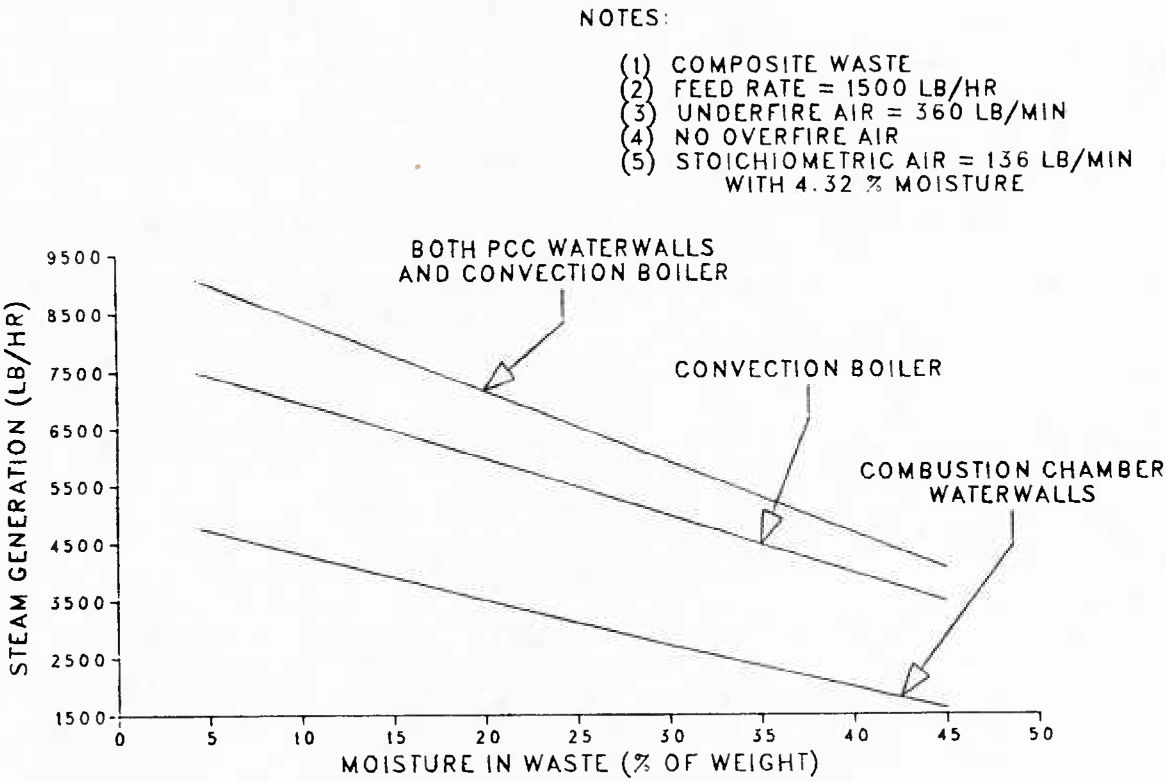


(a) Effect of moisture in the waste (fuel) on the steam generated.

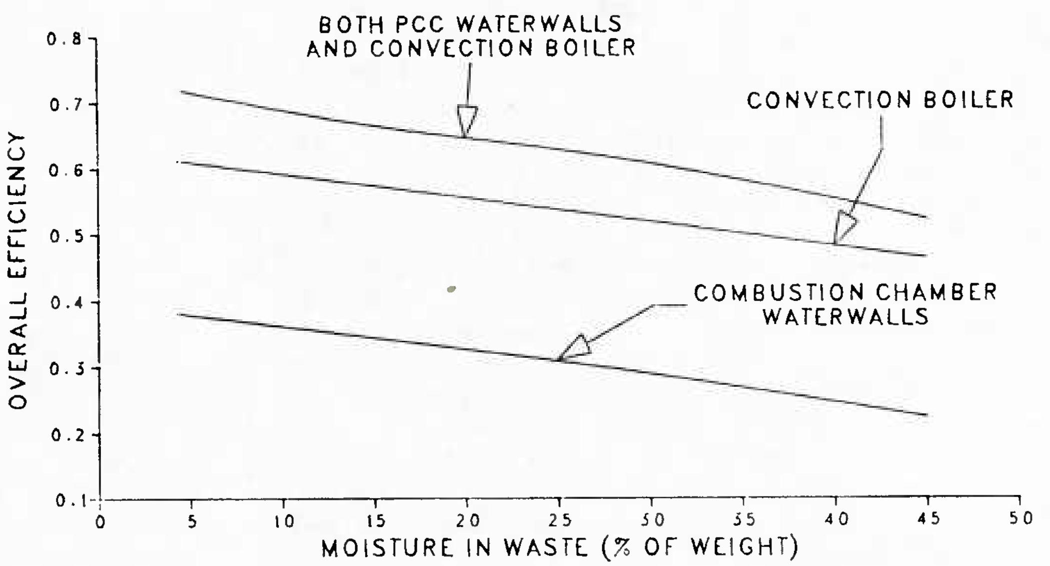


(b) Effect of moisture in the waste on the overall efficiency.

Figure 14. Starved air energy recovery incinerators.



(a) Effect of moisture in the waste on the steam generated.



(b) Effect of moisture in the waste on the overall efficiency.

Figure 15. Excess air energy recovery incinerators.

Another consideration is the effect of moisture on flame temperature. Figure 16 shows typical effects of moisture on the homogeneous flame temperature. In this example, a 20% increase in moisture produces a 300 to 400°F decrease in flame temperature.

Heat Transfer Characteristics

The resistance to conduction through the combustion chamber walls is, by far, the dominant resistance to heat transfer (losses) out of the incinerator. Figure 17 compares the resistance through the wall with the resistance to heat transfer through the boundary layers on each side of the wall. Changes in heat transfer resistances have been arbitrarily chosen; nevertheless, the influence of the conduction mode is obvious.

Heat transfer losses are not normally large. In Figure 17, the thickness of the walls has been decreased by one-half. Flame temperature is decreased by about 250°F under stoichiometric conditions. Total heat transfer losses are increased from 9 to 16% of the total energy input under stoichiometric conditions. These losses are increased from 7 to 12% of the total energy input under typical substoichiometric operating conditions.

Surprisingly, changes in the combustion chamber flow characteristics have only a minor effect on energy recovery.* Figures 17 (convection boiler configuration) and 18 (waterwall configuration) attempt to illustrate this, showing the effects that significant changes in the convection coefficient have on flame temperature. This observation suggests designing the combustion chamber for optimum combustion characteristics and taking whatever convection coefficients result.

The effect of the PCC wall convection coefficient on incinerator performance is shown in a different manner in Figure 19. Total heat transferred to the steam is the dependent variable; energy sources and heat transfer modes are parameters. Two key points can be made from this figure. First, net radiation from the flame is not appreciably affected by changes in the convection coefficients. Thus, as shown in previous figures, the flame temperature does not vary much. Second, combustion chamber flow characteristics have very little influence on steam generation. Increases in convection heat transfer from the PCC combustion products are balanced by decreases in radiation from the PCC gases and decreases in convection from the SCC gases (i.e., decreases in steam generation in the convection boiler). The problem is analogous to five resistances in parallel; a change in one is partially, but not completely, attenuated by opposite changes in the others because of the induced change in the potential (temperature difference).

Radiation shape factors (i.e., the relative geometry of the flame and waterwalls) play a small but not insignificant role in the operation of energy recovery incinerators. Figures 20 and 21 show the effect of the shape factor on temperatures and steam generation, respectively.

*This considers only heat transfer. Flow characteristics strongly influence the combustion process, which certainly influences energy recovery.

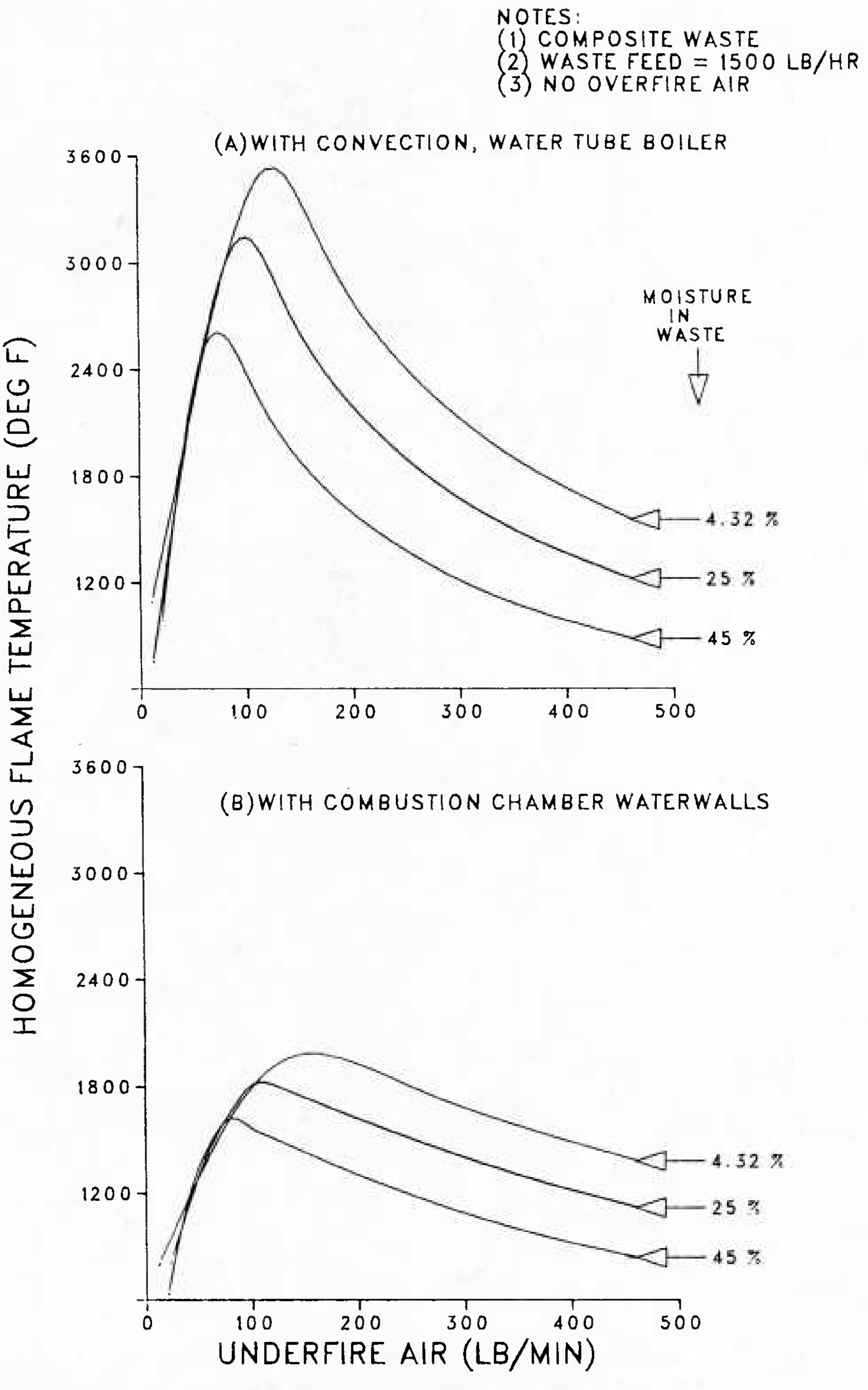


Figure 16. Effect of moisture in the waste on flame temperature of an energy recovery incinerator.

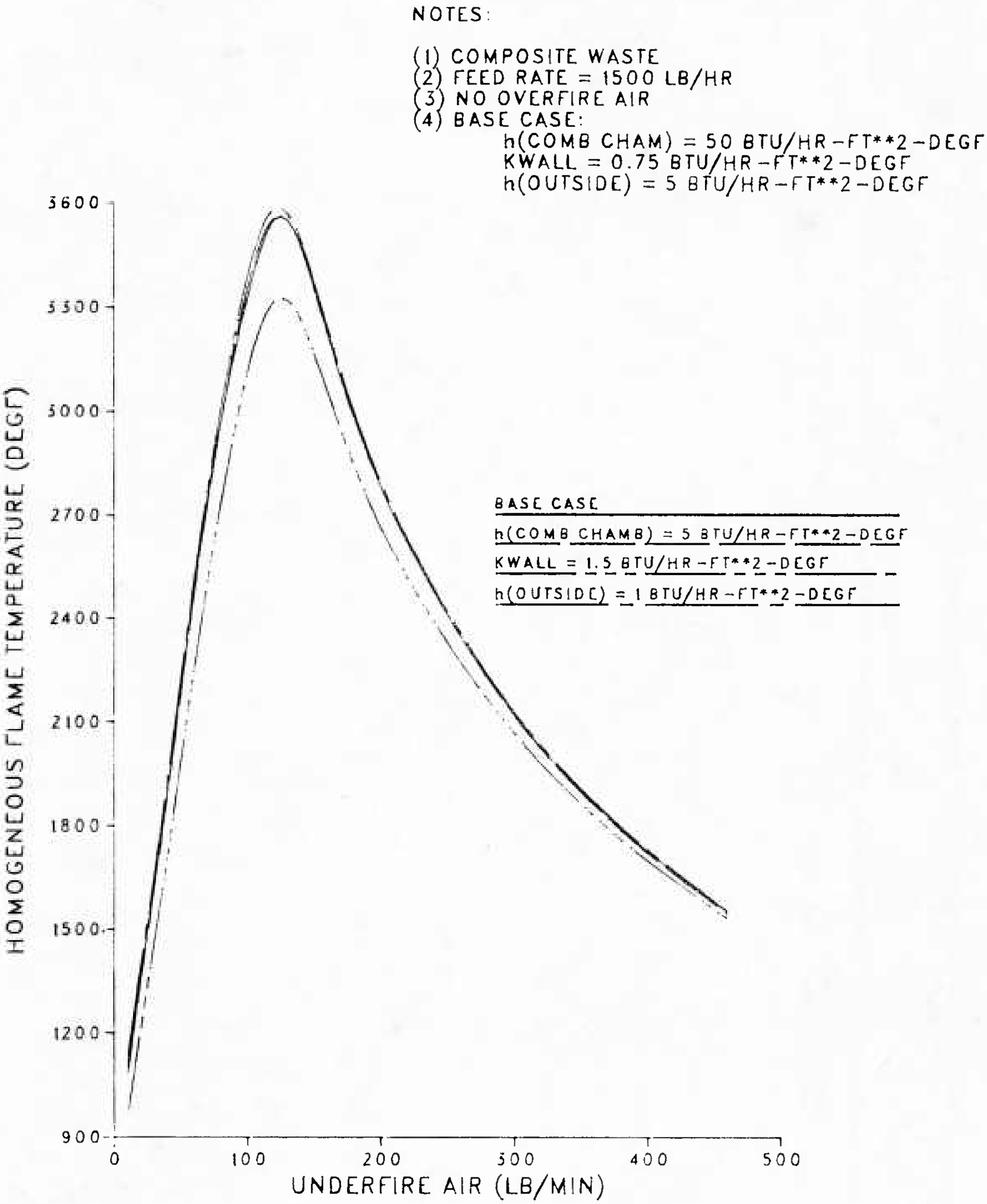


Figure 17. Effect of heat transfer characteristics on flame temperature of incinerator configurations without waterwalls.

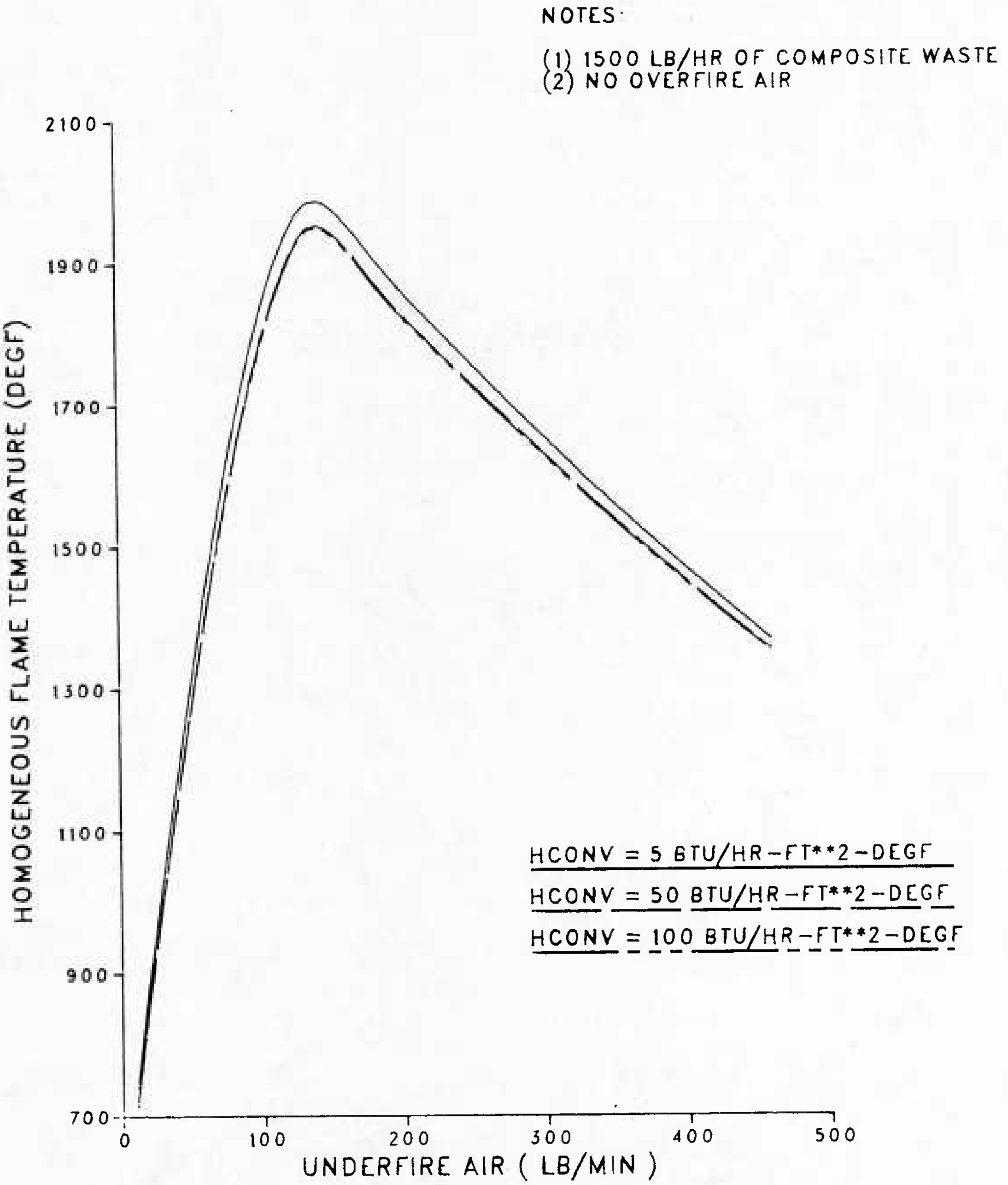


Figure 18. Effect of waterwall convection coefficient on incinerator flame temperature.

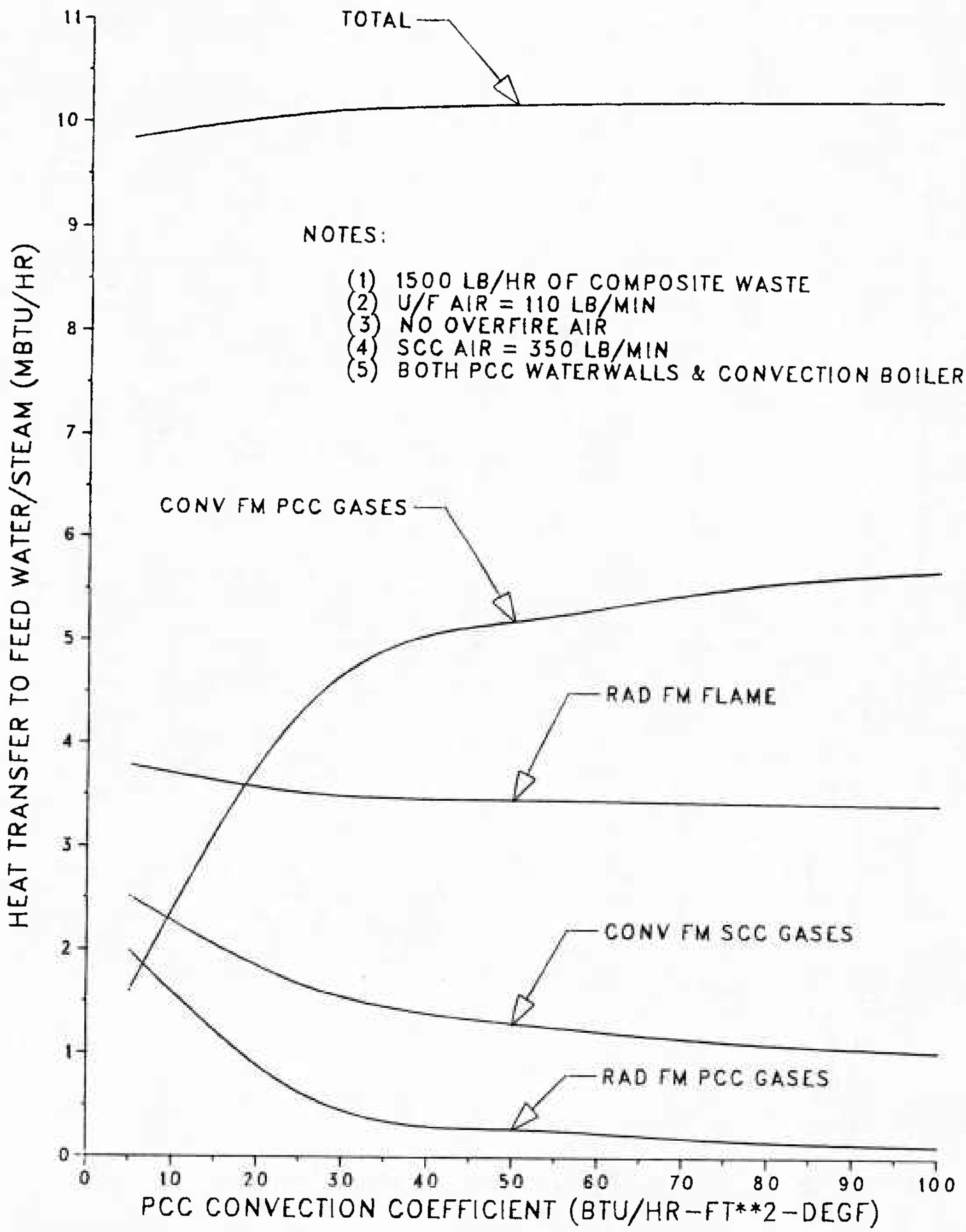


Figure 19. Effect of convection coefficient between PCC combustion products and waterwalls on heat transfer to boilers.

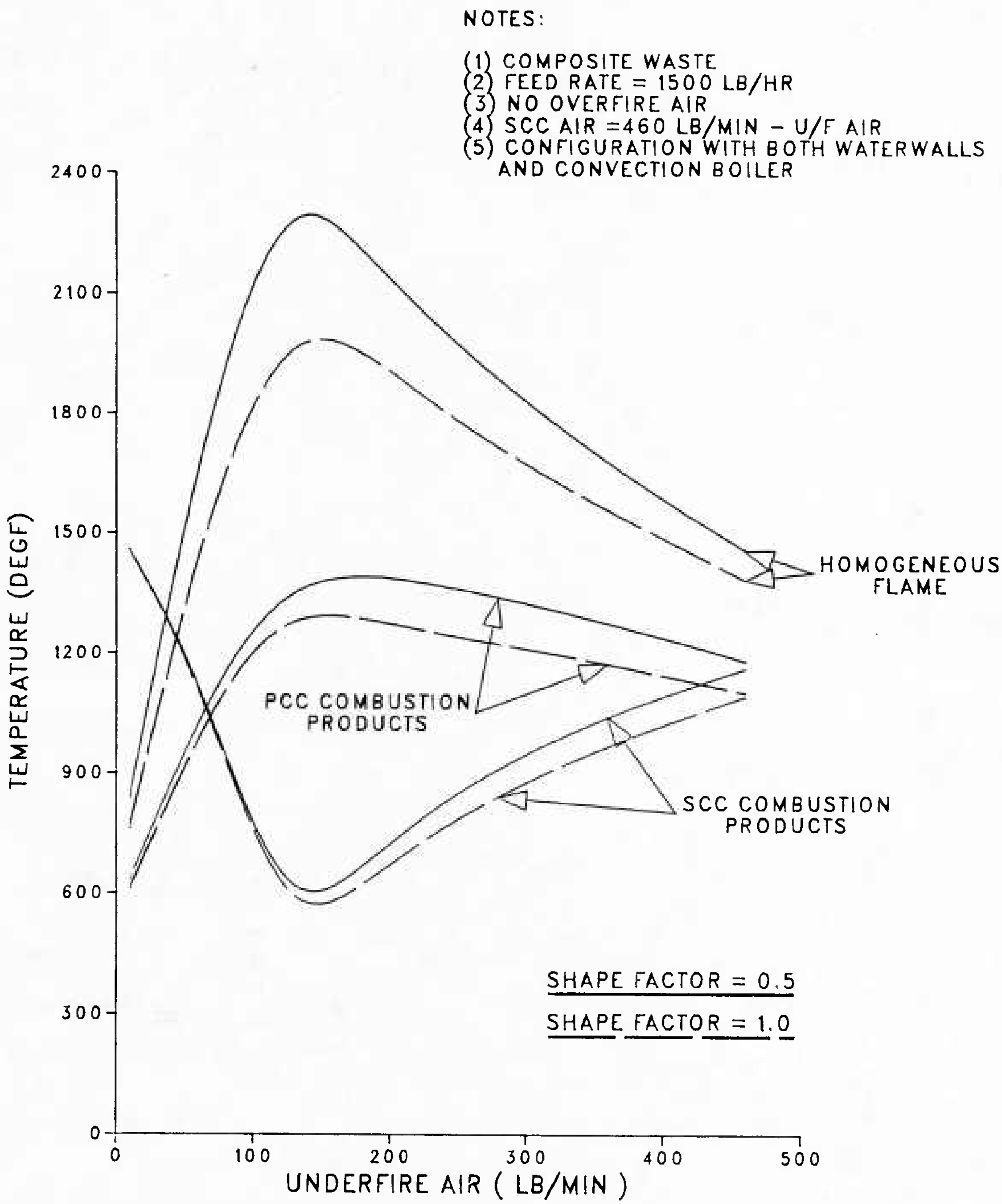


Figure 20. Effect of radiation shape factor between flame and waterwalls on incinerator combustion chamber temperatures.

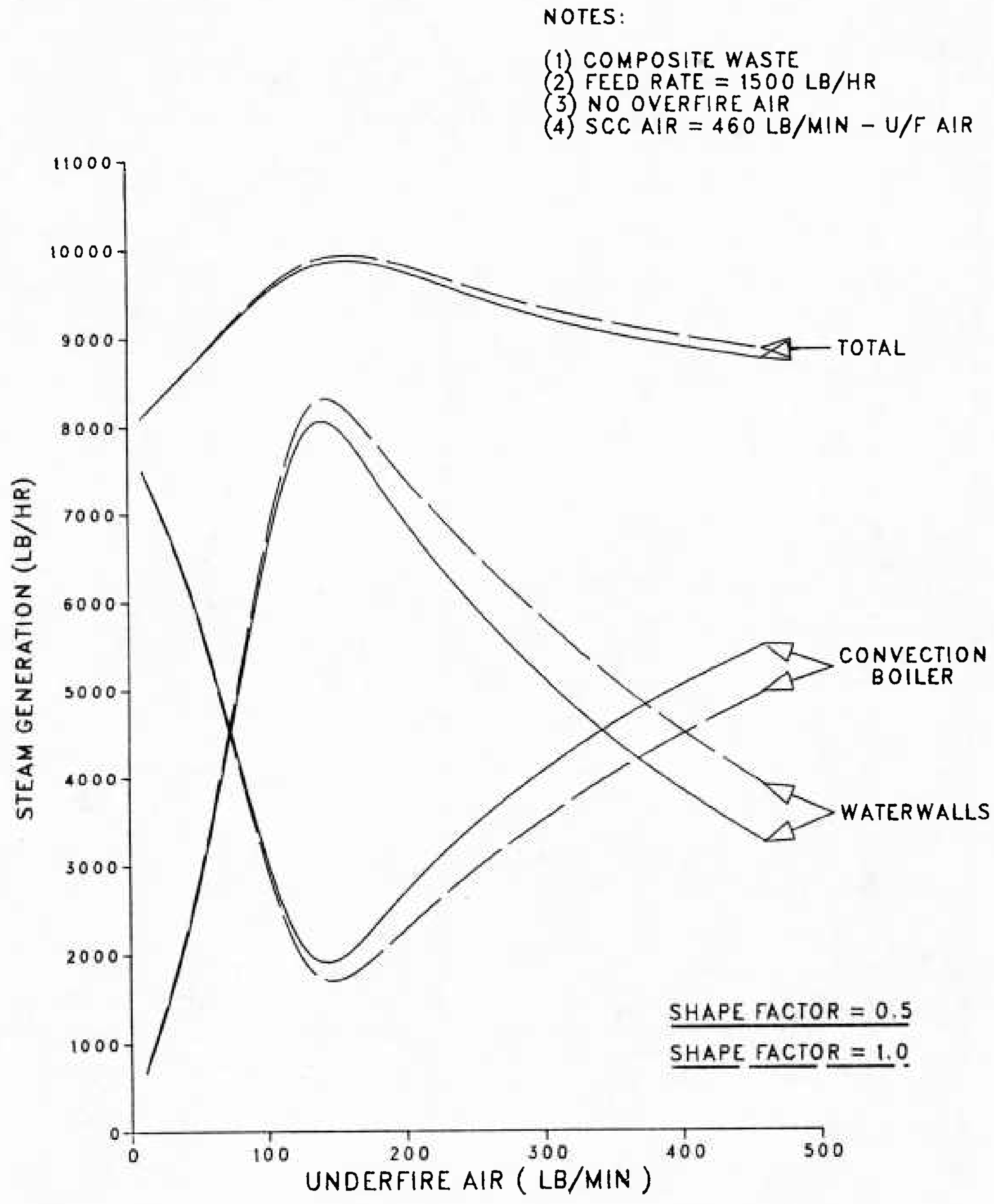


Figure 21. Effect of radiation shape factor between flame and waterwalls on incinerator steam generation rates.

Some control over flame temperature can be achieved by designing the PCC for optimum shape factors. This is probably the most difficult aspect of energy recovery design because of coupled effects on the convection coefficients and, most important, the combustion characteristics.

The effects of the shape factor on waterwall steam generation are important. When a convection boiler is added, however, the overall increase in energy recovery induced by improving the shape factor may not be significant. The SCC combustion gases are cooler when they arrive at the convection boiler, and steam generation in this device decreases.

Convection Boiler Performance

Convection heat transfer coefficients, covering the range encountered in actual water tube boilers, are used as the independent variable in Figures 22(a) and (b). The importance of the choice of heat exchangers is apparent; this topic will be discussed further in the next section.

The difference between the two figures is a change in SCC airflow. A comparison of (a) and (b) provides another example of the countering effects of temperature and mass flow rate on heat exchanger heat transfer and, therefore, steam generation. Figure 22(b) summarizes the performance of a convection boiler configuration with 270 lb/min of SCC air. With a UA* of about 20,000 Btu/hr-°F, the SCC temperature is about 1,952°F and steam generation approaches 9,800 lb/hr. Increasing the airflow by about 50%, summarized by Figure 22(a), decreases secondary combustion chamber temperatures by about 500°F and the logarithmic mean temperature difference across the boiler by 20% yet decreases steam generation to only 9,100 lb/hr, a decrease of about 7% (again, assuming a UA of 20,000 Btu/hr-°F).

Heat Exchanger System Design

Figures 23 and 24 are examples of the type of analysis required for optimizing incinerator energy recovery performance. They show the effects of tradeoffs between the waterwalls and convection type boiler, in this case using heat transfer area as the parameter. These curves assume areas and can only be considered as typical. Nevertheless, they illustrate the necessity for tradeoffs in the design. Consider the diminishing increase in efficiency and the increased cost associated with a major increase in the dimensions of either the waterwalls or convection boiler.

ENERGY RECOVERY CONFIGURATIONS

Each of the three candidate incinerators is examined separately. Operating characteristics are discussed, and the advantages and disadvantages of each configuration are amplified.

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*UA = overall heat transfer coefficient times heat transfer surface area.

NOTES:

(1) COMPOSITE WASTE
(2) WASTE FEED = 1500 LB/HR
(3) U/F AIR = 40 LB/MIN
(4) NO OVERFIRE AIR
(5) PCC TEMPERATURE = 1877 DEGF
(6) UA = OVERALL HEAT TRANSFER COEFFICIENT TIMES HEAT TRANSFER SURFACE AREA

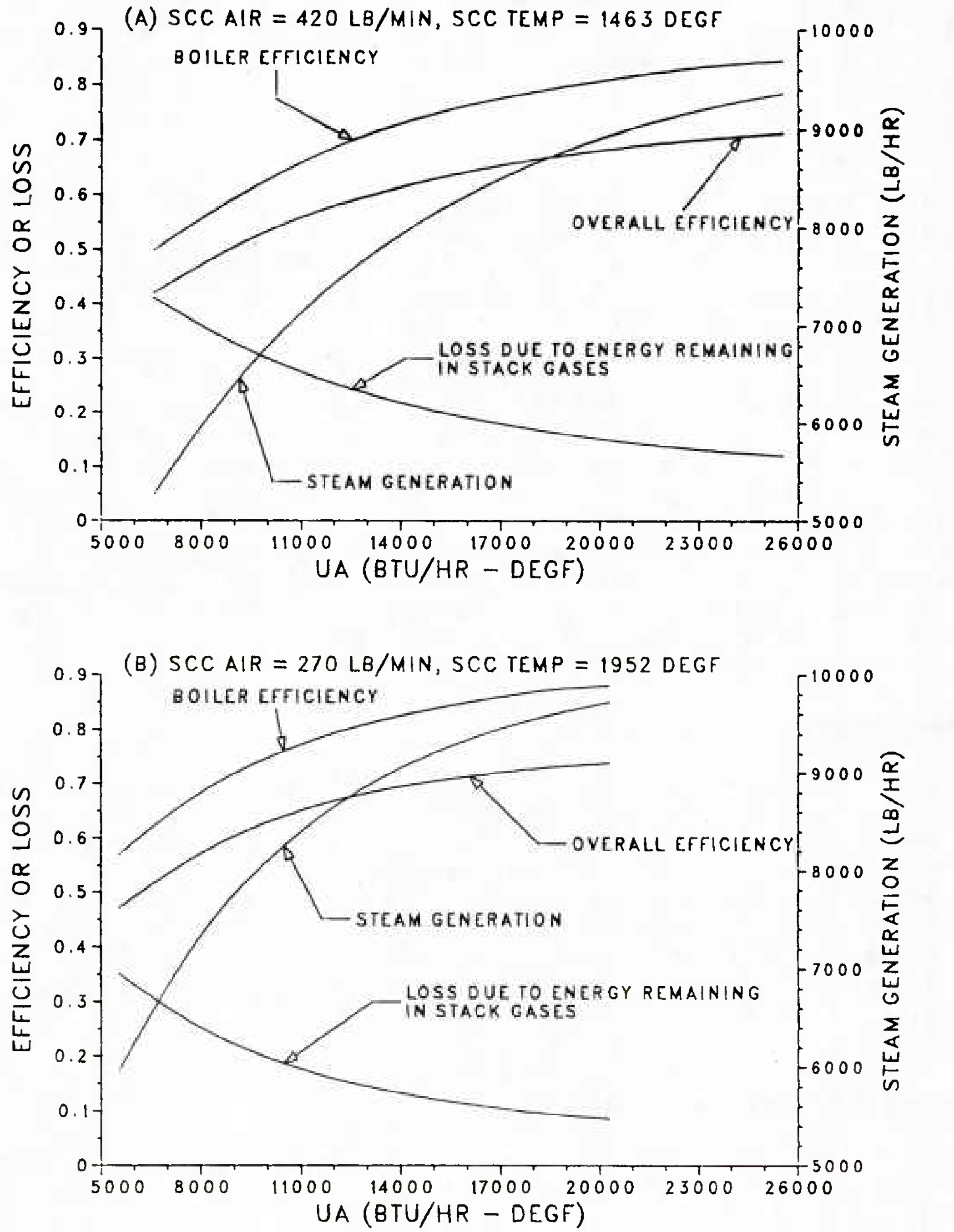

Figure 22. Effect of boiler performance on the overall performance of convection boiler type of energy recovery incinerator.

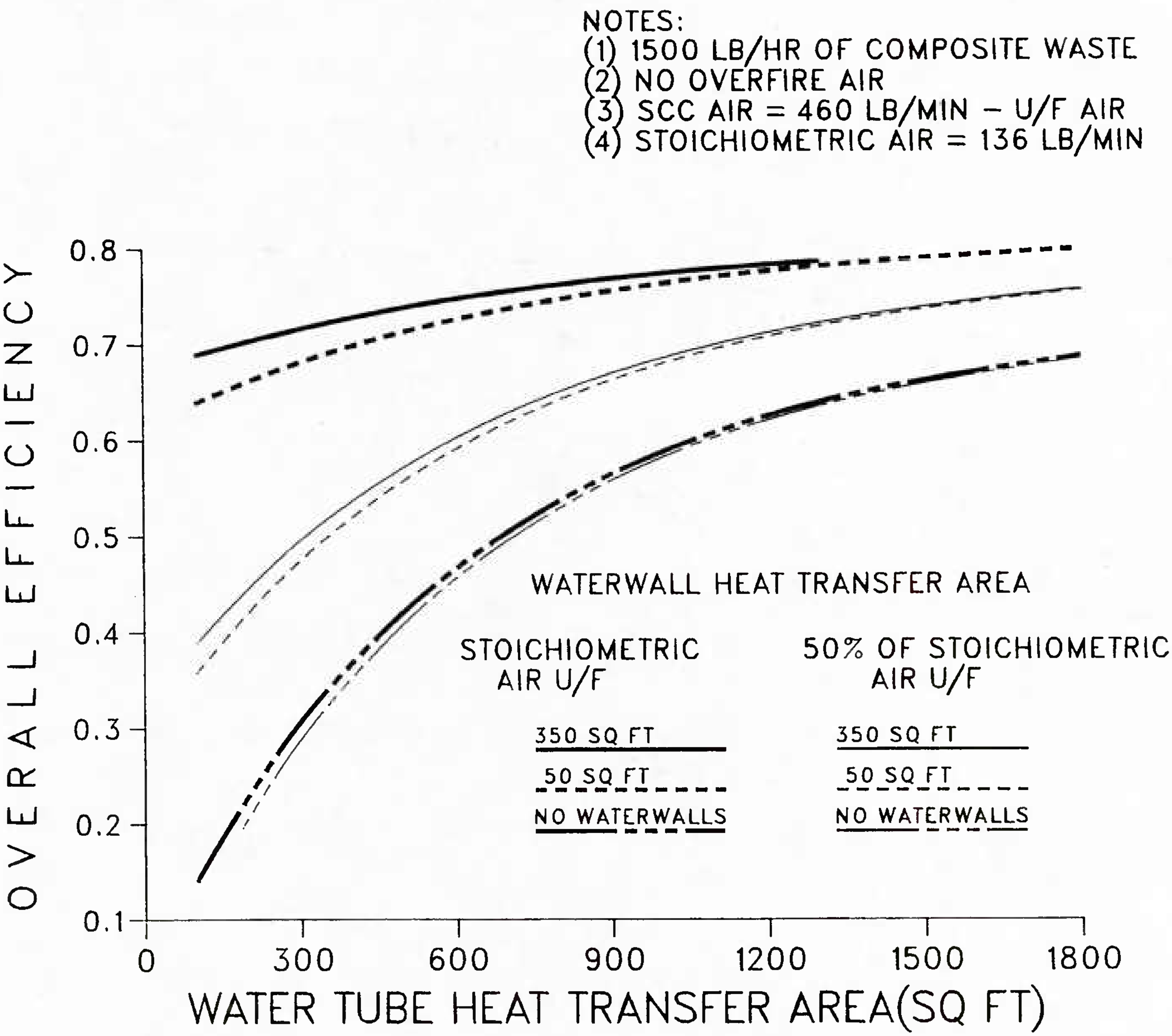

Figure 23. Effect of heat exchanger sizes on the performance of a starved air incinerator with both waterwalls and convection boiler.

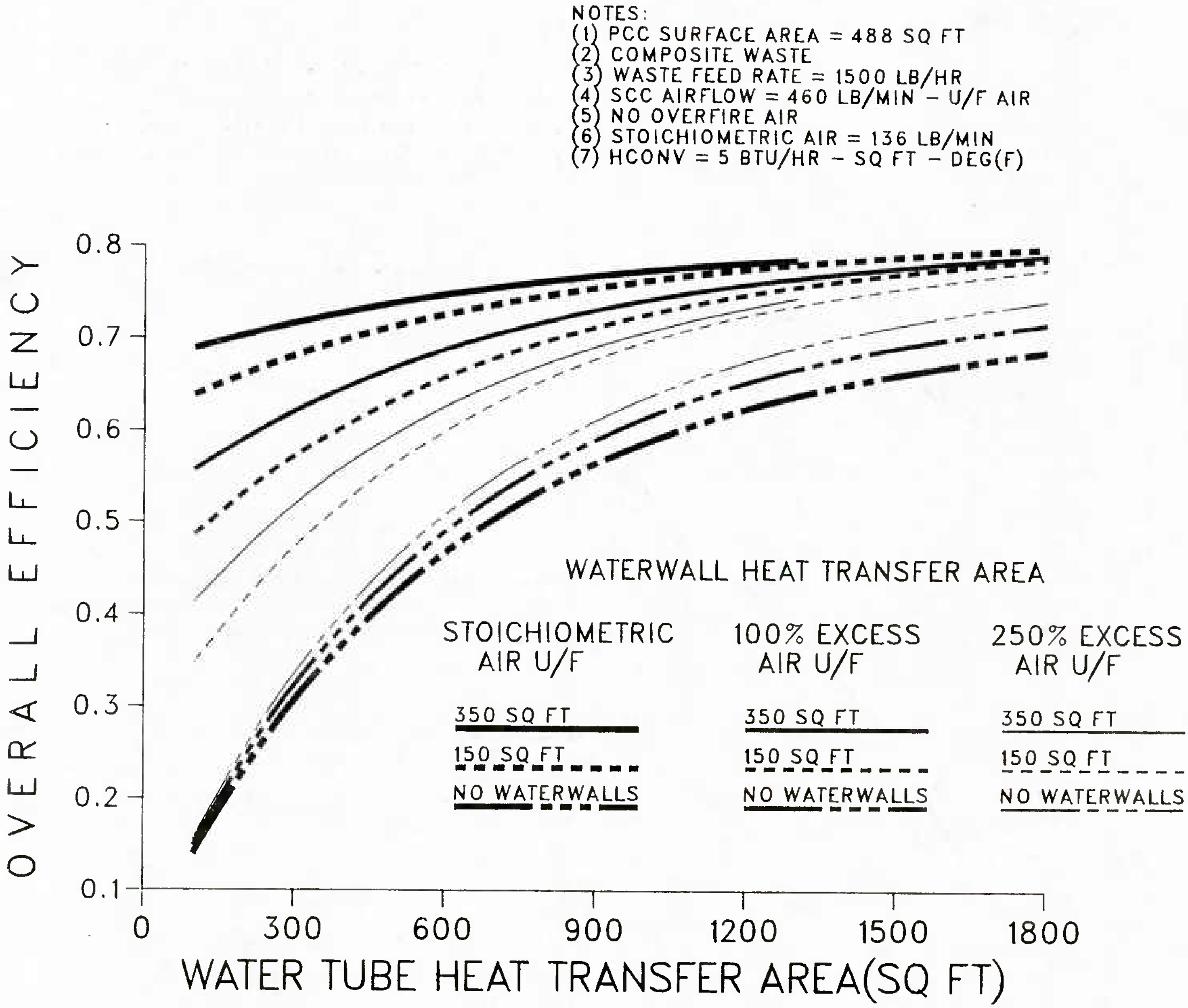

Figure 24. Effect of heat exchanger sizes on the performance of an excess air incinerator with both waterwalls and convection boiler.

Incinerators With Downstream Convection Boiler

Typical temperature profiles through an incinerator with a convection boiler are shown in Figure 25. Of primary significance is the high sensitivity of the flame temperature to changes to combustion airflow, in particular during starved air operation. The reason: very little energy is lost out of the primary combustion chamber. Most of the energy released during combustion is used for heating the products of combustion. Temperatures in these devices are also sensitive to other parameters, such as type and rate of the feed.

This figure also illustrates the difficulty of controlling this incinerator. Small changes in the operating parameters induce major changes in temperature to which the control system must respond, usually by changing the combustion air.

When total airflow into the incinerator is a constant, secondary combustion chamber temperatures remain approximately constant. This is the case for the incinerator summarized in Figure 25. All energy has been released, and all mass has entered the device by the time the SCC is exited. The only difference is minor PCC and hearth losses.

When total combustion air is varied by varying SCC air, as shown in Figure 6, the secondary chamber temperature varies considerably. The air, itself, has to be heated; the mass of this airflow affects both temperatures and heating rates.

Overall efficiencies follow the same trend. Figures 26 and 27 show this. With a constant energy and constant mass input to the boiler, the steam generation, and, therefore, the overall energy recovery efficiency, is constant. Vary the parameters (e.g., the combustion airflow) and temperature gradients are changed, inducing different steam generation rates.

The loss from sensible energy remaining in the stack gases is, by far, the major loss. This is the case with all configurations. It illustrates the advantage gained by reducing this loss by using some of this energy to (1) preheat the combustion air (see again Figure 7); (2) preheat the feed water (i.e., economizing); or (3) superheat the steam.

Incinerators With Waterwalls

Temperature profiles through a typical waterwall incinerator are represented in Figure 28. The important difference is a much lower flame temperature than occurs in incinerators without waterwalls, given the same conditions. In addition, the flame temperature is much less sensitive to changes in these conditions. Both are attributable to the higher heat transfer rates away from the flame, primarily radiation to the waterwalls.

Overall performance of waterwall incinerators is represented in Figure 29 for devices with only waterwalls and in Figure 30 for incinerators with both waterwalls and a downstream convection boiler. Adding the convection boiler has the obvious effect of stabilizing the performance of the waterwall incinerator. The efficiency of the convection boiler will tend to increase as the efficiency of the waterwalls drops. More internal thermal energy is retained by the air and combustion products reaching the convection boiler.

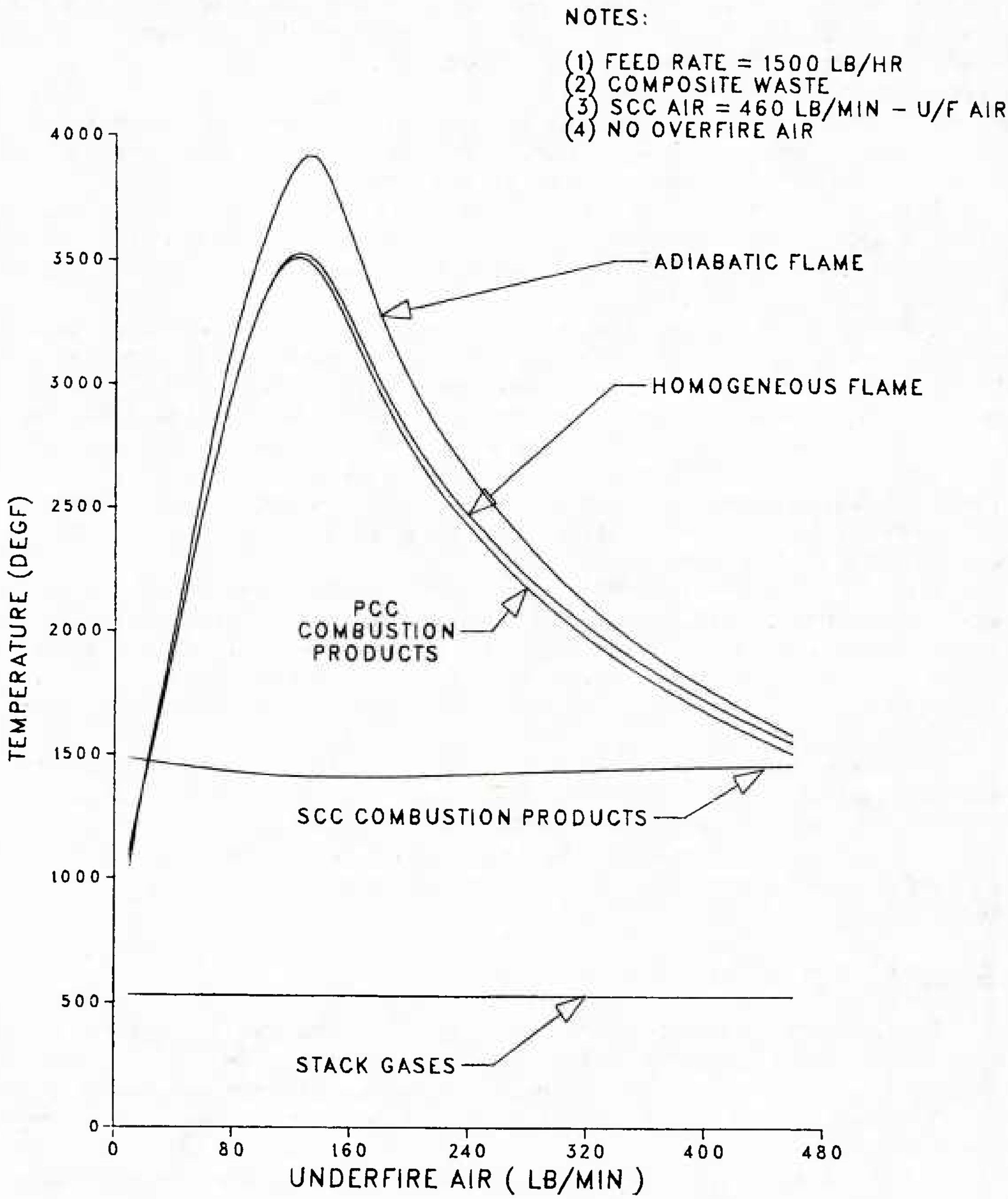

Figure 25. Typical temperature profiles through waste incinerator with convection, water tube boiler.

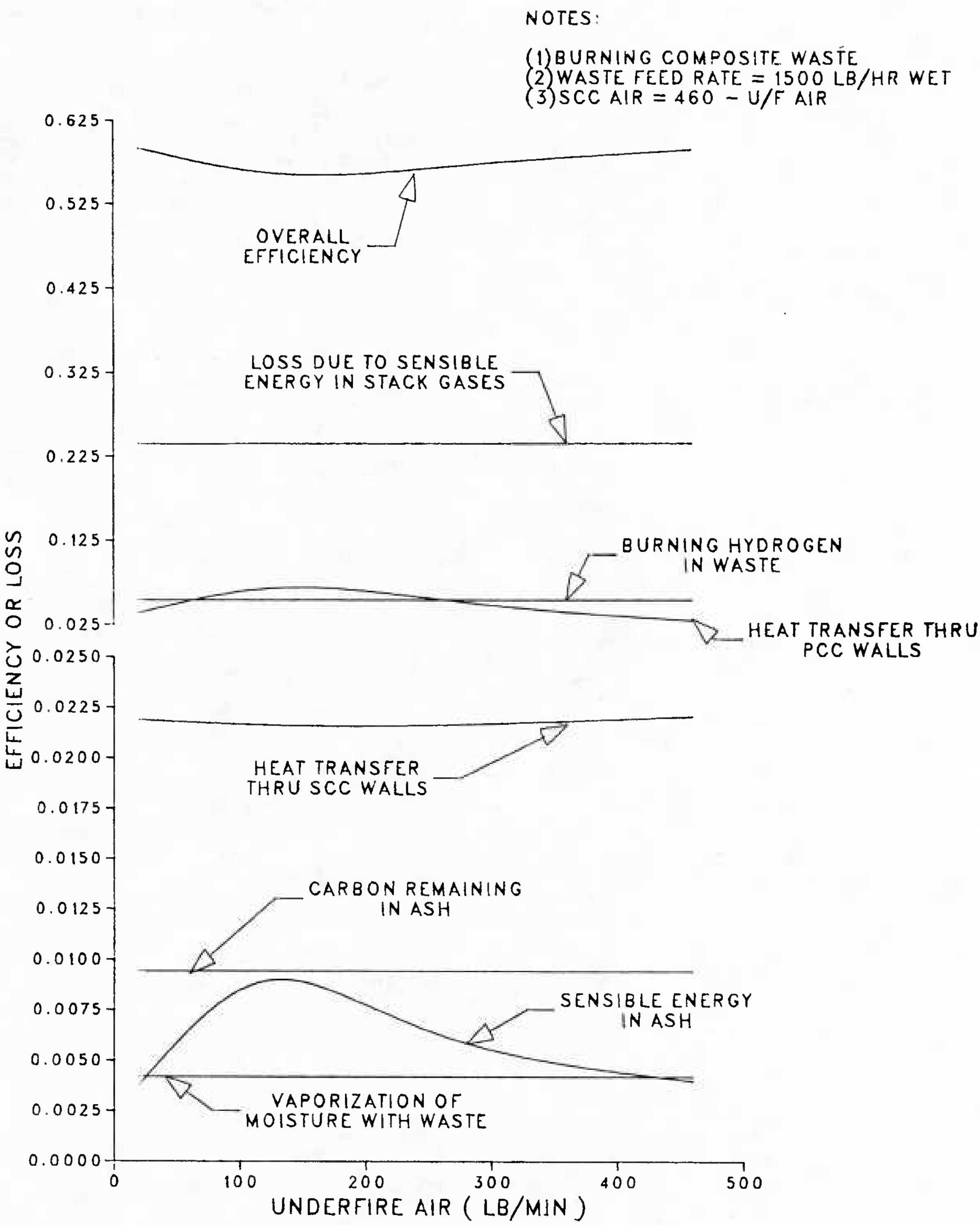

Figure 26. Typical performance of convection, water tube energy recovery incinerator.

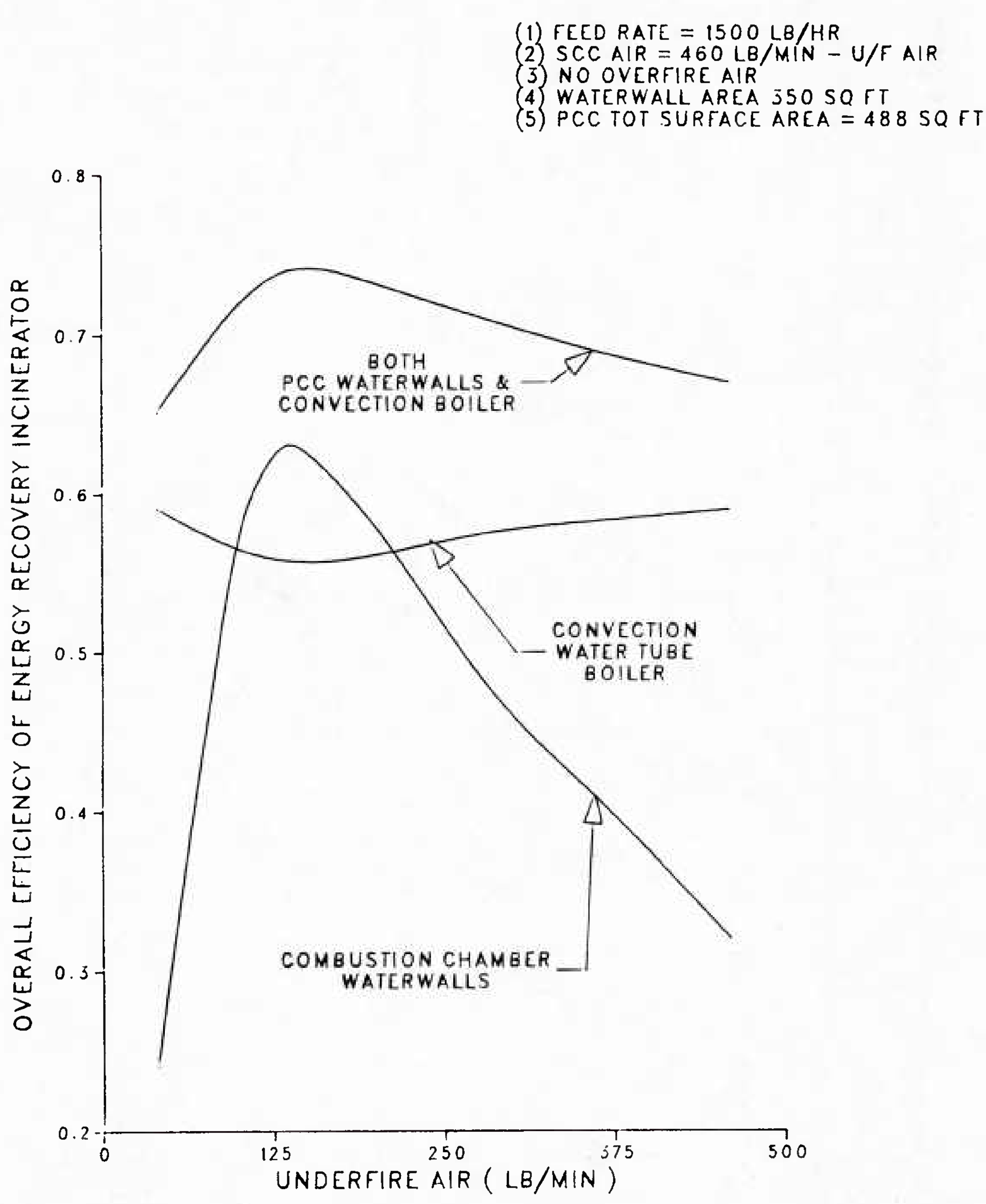

Figure 27. Comparison of the energy recovery efficiency of different incinerator configurations.

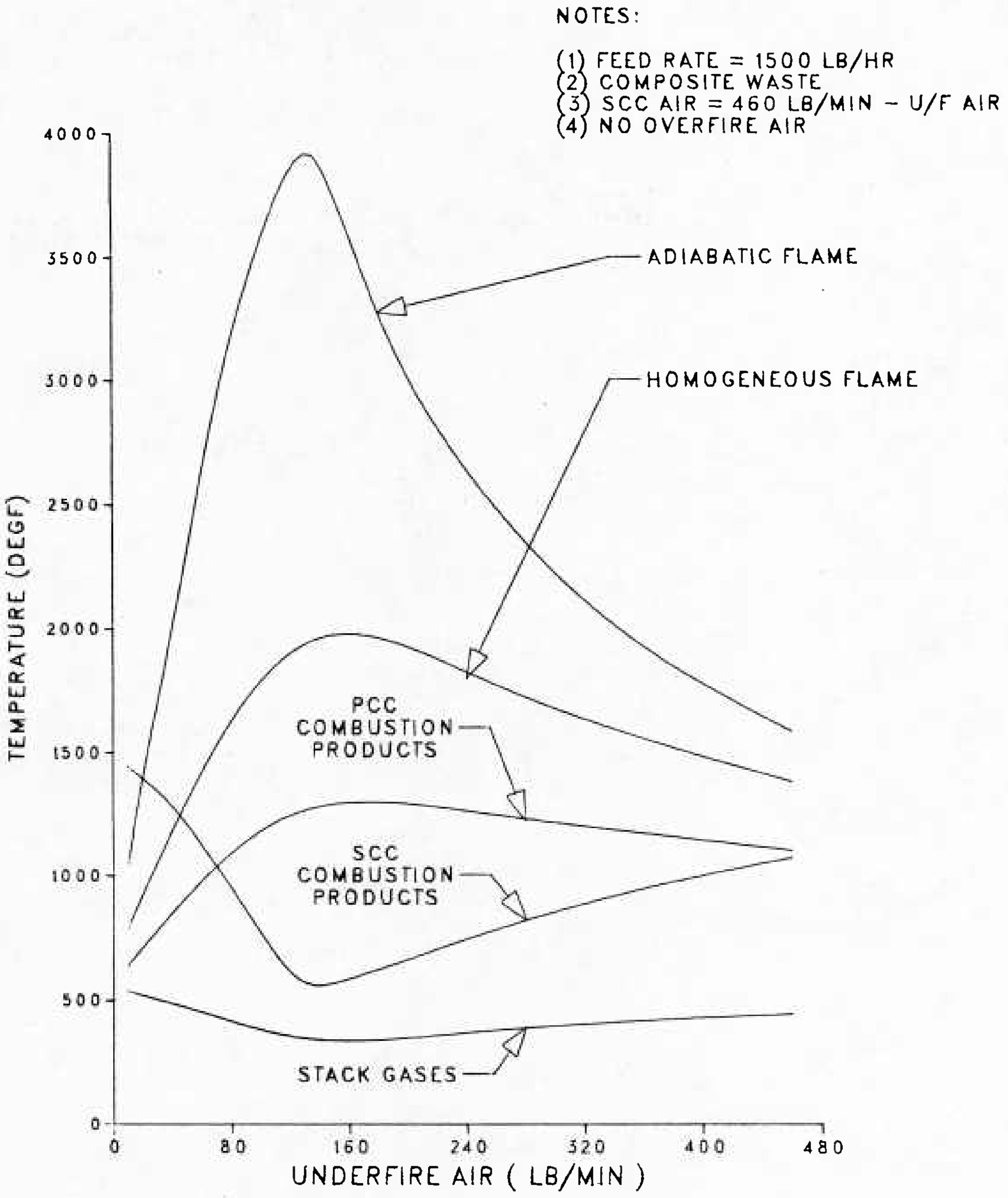

Figure 28. Typical temperature profiles through waste incinerator with both waterwalls and convection boiler.

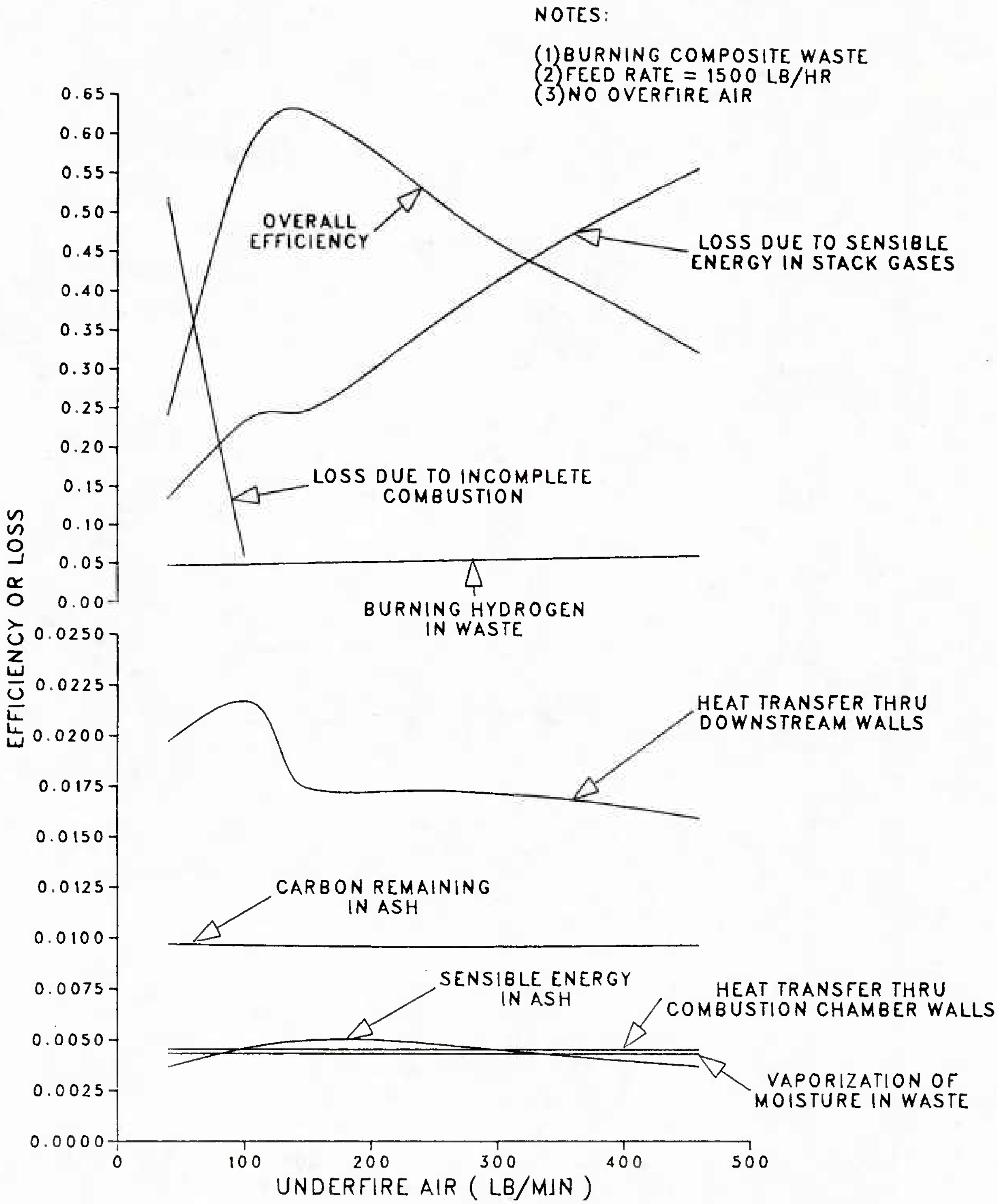

Figure 29. Typical performance of waterwall energy recovery incinerator.

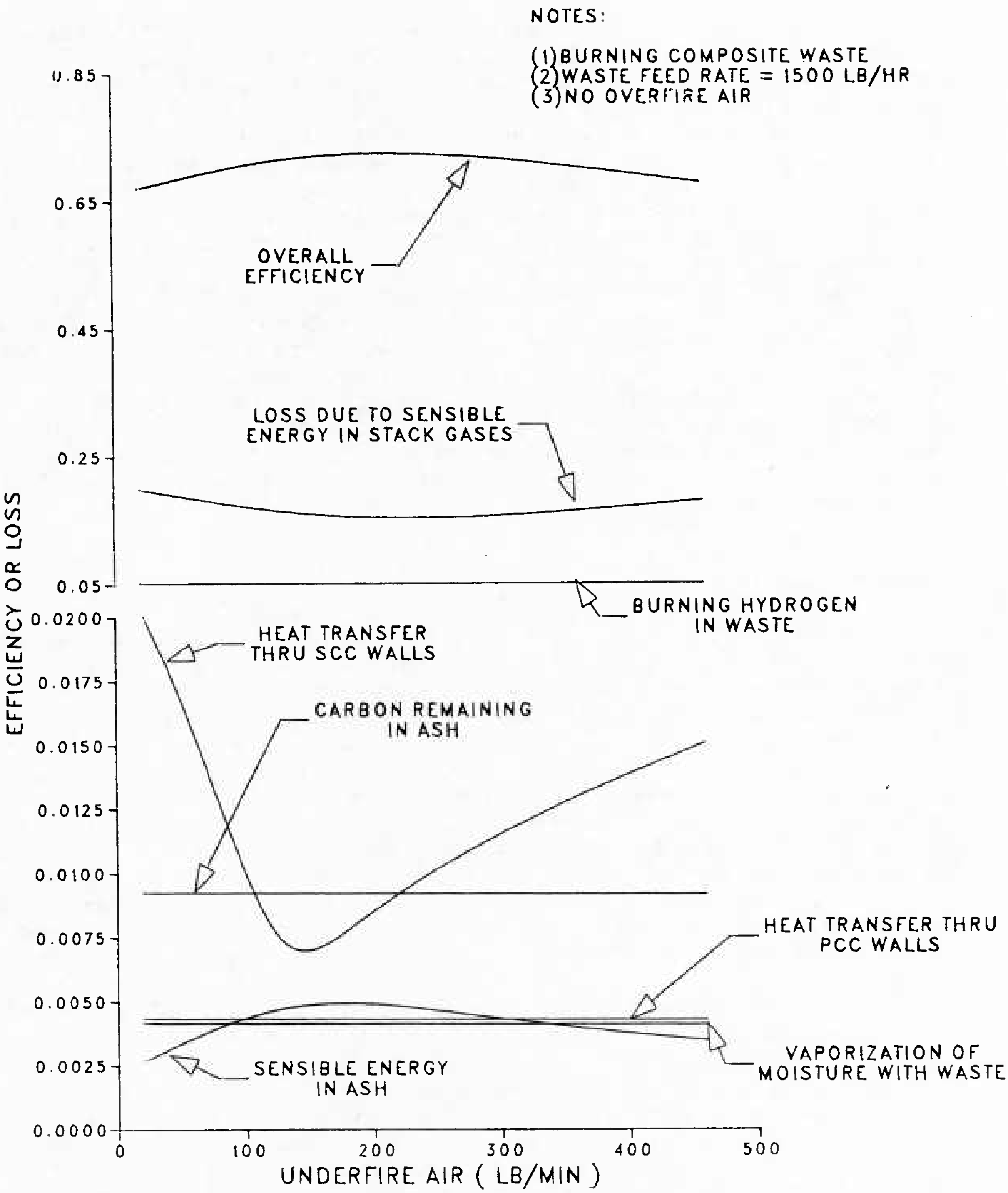

Figure 30. Typical performance of energy recovery incinerator with both waterwalls and convection boiler.

COMPARISON OF CONFIGURATIONS

Figures 27 and 31 show incinerator efficiencies and flame temperatures of the different configurations plotted together. The advantages of a configuration with both waterwalls and a convection boiler are apparent. Efficiencies are higher, although this would be expected with the increased total heat transfer area. Efficiencies are also more stable. Changes in flame and PCC conditions have the opposite effect on the performance of the waterwalls than on the performance of the convection boiler (i.e, the less energy radiated to the waterwalls, the greater the internal thermal energy of the combustion products as they arrive at the convection boiler).

Although a direct comparison of magnitudes is not valid since specific heat transfer areas are implied, flame temperatures are normally much lower when waterwalls are used. Flame temperatures are also more stable. As much as two-thirds of the energy release is transferred to the walls rather than going into increasing the internal thermal energy of the air and combustion products. Effects of changes in parameters that change the release of the enthalpy of combustion are reduced in magnitude; most of this change is reflected as a change in waterwall steam generation rates.

SUMMARY COMMENTS

The key corollary of this work is the stability and, hence, the operational benefits gained by using both waterwalls and a convection type of boiler in the energy recovery incinerator. Some other observations, not made in previous work of this type, are worth reemphasizing, however.

One example is the observation that maximum incinerator energy recovery efficiency might be acquired by designing the combustion chambers for optimum combustion efficiency and taking whatever heat transfer characteristics result. Heat transfer losses are relatively small. In particular, the minor role played by convection across the inside and outside wall boundary layers is noteworthy. Resistance to conduction through the wall dominates. The layout of the combustion chambers as they affect radiation plays a small role when a convection boiler is used.

The countering effects of temperature and velocity of the combustion gases as they pass through the convection boiler are significant, resulting in the relative insensitivity of the energy recovery incinerator to dump stack or SCC air leakage or changes in SCC combustion air.

A final observation is the difficulties that will be encountered in controlling starved air incinerators. The high oxygen content inherent in the waste results in low stoichiometric air requirements (Ref 4), perhaps half the air required for the combustion of the same amount of coal. It follows that small changes in incinerator parameters (e.g., combustion air) produce large changes in, for example, temperature. In addition, the heterogeneous nature of the fuel tends to induce excursions between starved and excess air operation. The operating mode must be identifiable. This requires complicated controls, specifically, the need for the input of several temperatures or perhaps a gas composition.

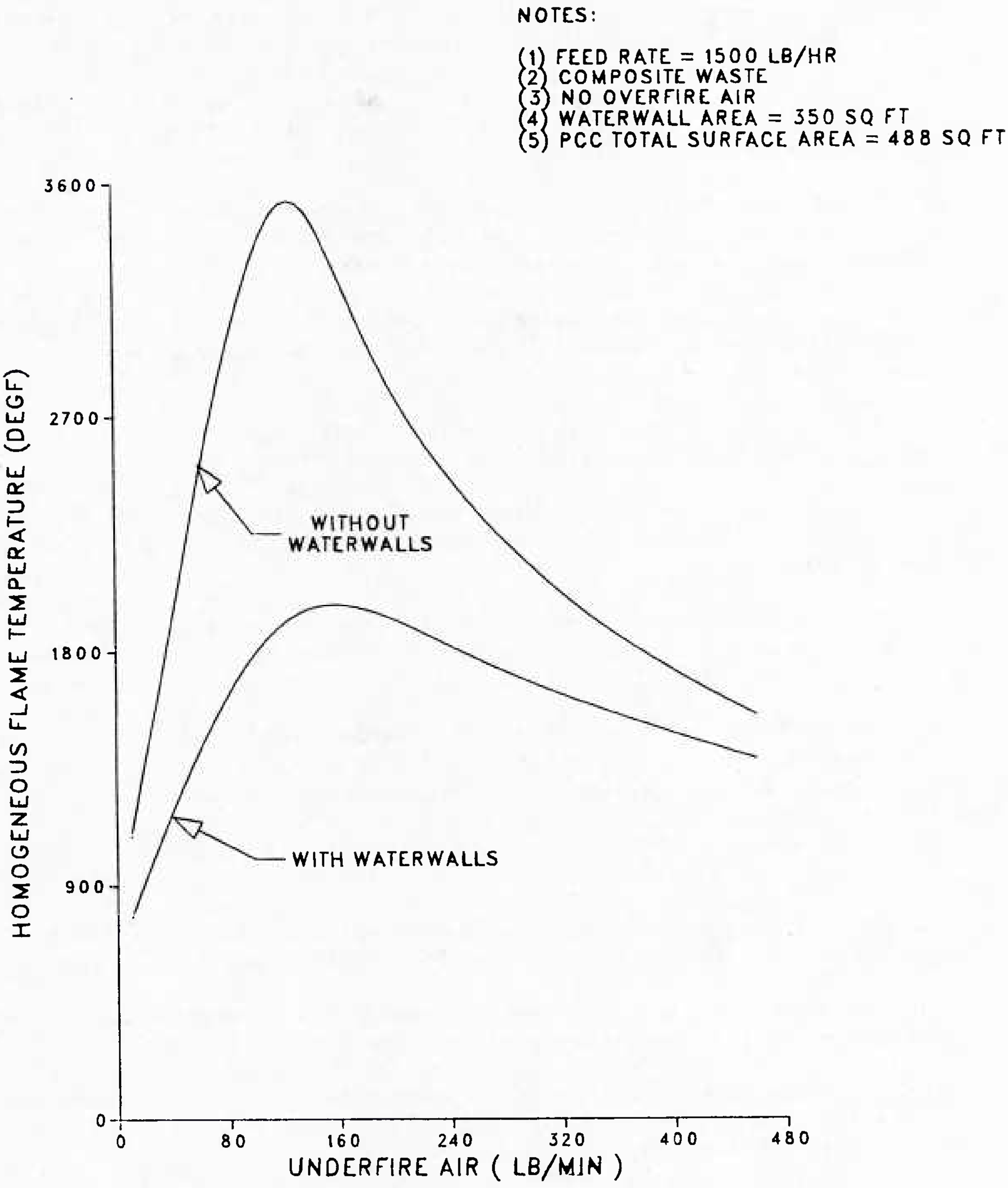

Figure 31. Effect of waterwalls on incinerator flame temperature.

REFERENCES

1. Environmental Protection Agency. Contract Report EPA-670/2-73-089A: Design and control of incinerators, by A.F. Sarofim et al. Cambridge, Mass., Massachusetts Institute of Technology, Sep 1973.

2. H.H. Krause, D.A. Vaughan, and P.D. Miller. "Corrosion and deposits from combustion of solid waste," Journal of Engineering for Power, vol 95, Jan 1973, pp 45-52.

3. Naval Civil Engineering Laboratory. Technical Note N-____: Computer program to simulate the thermal characteristics of heat recovery incinerators, by C.A. Kodres. Port Hueneme, Calif. (in publication).

4. ____________. Technical Note N-1659: A parametric examination of the heat recovery incinerators at NAS Jacksonville, by C.A. Kodres. Port Hueneme, Calif., Mar 1983.

5. W.P. Kramer. "The capabilities and limitations of current incinerator designs," Public Works, Jul 1970, pp 57-59.

6. J.W. Regan. "Generating steam from prepared refuse," in Proceedings of the 1970 National Incinerator Conference, Cincinnati, Ohio, May 1970, pp 216-223.

7. R.E. McRee. "Waste heat recovery from packaged incinerators," in Incinerator and Solid Waste Technology, edited by J.W. Stephenson. New York, N.Y., American Society of Mechanical Engineers, 1975, pp 357-374.

8. National Bureau of Standards. Report NBSIR 84-2938: Chemical processes during the starved air incineration of municipal solid waste, by W. Tsang and J.A. Walker. Washington, D.C., Oct 1984.

9. I. Glassman. Combustion, first edition. New York, N.Y., Academic Press, 1977, Chapter 9.

10. A.M. Kanury. Introduction to combustion phenomena, first edition. New York, N.Y., Gordon and Breach, 1982, Chapter 6.

11. American Society of Mechanical Engineers. Power Test Code PTC 4.1: Test code for steam generating units. New York, N.Y., 1964.

12. National Bureau of Standards. Report NBSIR 78-1479: Thermodynamic data for waste incineration, by E.S. Domalski, W.H. Evans, and T.L. Jobe. Washington, D.C., Aug 1978.

13. Georgia Institute of Technology. Bulletin 2: Instantaneous values of specific heat, by R.L. Sweigert and M.W. Beardsley. Atlanta, Ga., 1938.

14. W.H. McAdams. Heat transmission. New York, N.Y., McGraw-Hill, 1954.

15. J.O. Hirschfelder, C.F. Curtiss, and R.B. Bird. Molecular theory of gases and liquids. New York, N.Y., John Wiley, 1954.

16. J.M. Ortega and W.C. Rheinboldt. Iterative solution of nonlinear equations in several variables, first edition. New York, N.Y., Academic Press, 1970, Chapter 7.

17. Naval Civil Engineering Laboratory. Contract Report CR 81.012: Test and evaluation of the heat recovery system at Naval Station, Mayport, Fla. Xenia, Ohio, Systech Corp., May 1981. (Contract No. N68305-80-C-0006)

18. National Aeronautics and Space Administration. SP-273: Computer program for calculation of complex chemical equilibrium compositions, rocket performance, incident and reflected shocks and Chapman-Jouguet detonations, by S. Gordon and B.J. McBride. Washington, D.C., Mar 1976.

Appendix A

BASELINE ESTABLISHED FOR PARAMETRIC EXAMINATION OF ENERGY RECOVERY INCINERATORS

The following magnitudes of incinerator variables establish the baseline around which the parametric examination is conducted. Unless otherwise specified, they can be considered as input to the analyses.

GENERAL TO ALL CONFIGURATIONS

Fuel

Composite waste (see Appendix B)
Feed rate = 1,500 lb/hr

Ash

Removal rate = 200 lb/hr
Higher heating value = 1,417 Btu/hr
Ultimate analysis (percent by dry weight)

Carbon	5.00
Other	95.00

Oil as Auxiliary Fuel

To primary combustion chamber = 0 lb/hr
To secondary combustion chamber = 16 lb/hr
Higher heating value = 19,700 Btu/lb
Ultimate analysis (percent of dry weight)

Carbon	86.00
Hydrogen	12.00
Oxygen	0.50
Nitrogen	0.00
Other	1.50

Combustion Air

Total output of blowers = 460 lb/min
With primary oil burner = 0
With secondary oil burner = 12 lb/min

Leakage Air

To primary combustion chamber = 10 lb/min
To secondary combustion chamber = 0
Down the dump stack = 10 lb/min

Heat Transfer Parameters

Ambient air temperature = 70°F
Surface area of flame = 112 ft^2
Surface area of SCC = 360 ft^2
Emissivity of outer skin = 0.75
Film coefficient of outer skin = 5 Btu/hr-ft^2-°F
Thermal conductance through walls
    Of primary combustion chamber = 0.75 Btu/hr-ft^2-°F
    Of secondary combustion chamber = 0.75 Btu/hr-ft^2-°F
Mean beam length
    Of primary combustion chamber = 4.7 ft
    Of secondary combustion chamber = 3.9 ft

Steam

Feed water properties
    Temperature = 227°F
    Enthalpy = 195 Btu/lb
Steam properties
    Temperature = 353°F
    Pressure = 140 psia
    Enthalpy = 1,193 Btu/lb
Boiler blowdown = 2% of steam generated

Power Requirements

Blowers, pumps, waste processing equipment, etc. = 100 kW

WATERWALL CONFIGURATIONS

Heat Transfer Parameters

Waterwall heat transfer area = 350 ft^2
Convection film coefficients
    Waterwall surface = 5 Btu/hr-ft^2-°F
    Inner surface of SCC = 5 Btu/hr-ft^2-°F

CONVECTION BOILER CONFIGURATIONS

Heat Transfer Parameters

Surface area of PCC = 488 ft^2
Convection film coefficients
Inner surface of PCC = 50 Btu/hr-ft^2-°F
Inner surface of SCC = 50 Btu/hr-ft^2-°F

Boiler Characteristics

Surface area of tubes = 968 ft^2
Design point
Inlet gas temperature = 1,800°F
Exit gas temperature = 500°F
Gas flow rate = 17,000 lb/hr
Overall heat transfer coefficient = 9.24 Btu/hr-ft^2-°F

Appendix B

COMPOSITION OF WASTE ASSUMED FOR PARAMETRIC EXAMINATION OF ENERGY RECOVERY INCINERATORS

Table B-1 summarizes the compositions of the different types of waste considered in these studies (Ref 4). The samples analyzed were acquired at the Naval Air Station, Jacksonville during September 1980. Except for a low moisture content, indigenous to the Jacksonville area, the sample components compare closely with other data of this type (Ref 12).

For purposes of establishing a baseline, a "composite" sample was formed. The composition of this sample is as follows (percent by weight):

Paper	34.7
Corrugated Boxes	27.9
Plastics	14.8
Food Waste	17.1
Textiles	1.2
Grass	2.1
Wood	2.2

Table B-1. Assumed Composition of Waste (percent by weight)

Ultimate Analysis (dry)	Type of Waste					
	Paper	Plastics	Food Waste	Grass	Wood	Composite
Carbon	39.54	81.36	46.25	40.43	45.65	47.56
Hydrogen	6.14	7.91	6.78	5.81	6.07	6.22
Oxygen	52.47	10.41	33.25	42.97	45.61	43.84
Nitrogen	0.13	0.05	2.20	1.35	0.20	0.09
Other	1.72	0.27	11.52	9.44	2.47	2.29
Moisture	7.93	0.05	48.95	24.56	8.07	4.32
Heating Value, 8,249 Btu/lb dry	7,522	17,390	9,704	8,692	8,375	8,957

Appendix C

MATHEMATICAL MODELING OF ENERGY RECOVERY INCINERATORS (Ref 3)

The simulation of the energy recovery incinerators is based on the hypothesized combustion reaction*:

$$C_{n_1}H_{n_2}O_{n_3}N_{n_4} + n_5H_2O + n_6O_2 + 3.76\ n_6N_2 \rightarrow$$

$$n_7CO_2 + (n_5 + n_8)\ H_2O + n_9CO + n_{10}O_2$$

$$+ (0.5\ n_4 + 3.76\ n_6)\ N_2 + n_{11}H_2 + n_{12}C \qquad (1)$$

In addition, it is assumed that:

1. Steady state exists.
2. Kinetic and potential energy changes are negligible.
3. The reactions go to completion regardless of the temperature.
4. The products of combustion are perfectly mixed.
5. All temperature gradients are normal to the incinerator walls; individual components of the incinerator can be represented one dimensionally.
6. The incinerator is operating at atmospheric pressure.
7. All gases are ideal.
8. The flame does not touch the wall. (The flame is defined as the region influenced by underfire air.)
9. There is always enough energy released to pyrolyze the waste.
10. Both the flame and the inside of the combustion chambers act as black bodies. The products of pyrolysis/combustion are gray.

*No attempt is made to distinguish between subscripts and coefficients. Numerical values are of interest here (i.e., number of moles), and both contribute in the same manner.

The molar coefficients n_1 through n_5 are obtained from ultimate and proximate analyses of the fuel (waste); n_6 is from the air supplied for combustion. For starved air operation, Equation 1, is balanced by applying conservation of species and allocating available oxygen linearly to the hydrogen and carbon in such a manner that the combustion of both elements is complete exactly when stoichiometric conditions are reached,

$$n_2H + X_1\left(n_6 + \frac{n_3}{2}\right) O_2{}^* \rightarrow 2\,X_1\left(n_6 + \frac{n_3}{2}\right) H_2O$$

$$+ \left[\frac{n_2}{2} - 2\,X_1\left(n_6 + \frac{n_3}{2}\right)\right] H_2$$

$$n_1C + X_2\left(n_6 + \frac{n_3}{2}\right) O_2 \rightarrow 2\,X_2\left(n_6 + \frac{n_3}{2}\right) CO$$

$$+ \left[n_1 - 2\,X_2\left(n_6 + \frac{n_3}{2}\right)\right] C \quad , \quad 2\,X_2\left(n_6 + \frac{n_3}{2}\right) < n_1$$

$$n_1C + X_2\left(n_6 + \frac{n_3}{2}\right) O_2 \rightarrow 2\left[n_1 - X_2\left(n_6 + \frac{n_3}{2}\right)\right] CO$$

$$+ \left[2\left(X_2\, n_6 + \frac{n_3}{2}\right) - n_1\right] CO_2 \quad , \quad 2\,X_2\left(n_6 + \frac{n_3}{2}\right) \geq n_1$$

where:

$$X_1 \equiv \frac{n_2/4}{n_1 + n_2/4}$$

$$X_2 \equiv \frac{n_1}{n_1 + n_2/4}$$

Stoichiometric air $\propto n_1 + n_2/4$

Carbon reacts with the oxygen to form carbon monoxide (Ref 9); any oxygen remaining oxidizes the carbon monoxide to form carbon dioxide. For excess air operation, water vapor and carbon dioxide are considered to be the only products of combustion.

*The program actually allocates the elemental oxygen rather than O_2.

STOICHIOMETRIC AIR

Stoichiometric air is the air required to oxidize the fuel to water vapor and carbon dioxide,

$$n_{7,STOICH} = n_1 \quad , \quad n_{8,STOICH} = \frac{n_2}{2}$$

$$n_{6,STOICH} = \frac{2\, n_{7,STOICH} + n_{8,STOICH} - n_3}{2}$$

$$\dot{M}_{AIR,STOICH} = [32 + 3.76(28)]\, n_{6,STOICH}\, \dot{M}_{FUEL,\ DRY}$$

where $\dot{M}_{FUEL,DRY}$ is the feed rate of the waste (dry).

HEAT OF PYROLYSIS

The heat absorbed in breaking down the fuel is primarily a heat of pyrolysis since most types of waste (e.g., paper and wood) are pyrolyzing solids. Regardless of the mode, the energy required to break down the fuel is easily calculated once the stoichiometric products of combustion have been determined,

$$Q_{FUEL} = HHV_{FUEL,DRY} - n_{7,STOICH}\, Q_{CO_2} - n_{8,STOICH}\, Q_{H_2O}$$

where: HHV = higher heating value of fuel (dry)

Q_{CO_2} = heat of formation of carbon dioxide

Q_{H_2O} = heat of formation of water (liquid)

ADIABATIC FLAME TEMPERATURE

If all the energy released during the combustion reaction is assumed to be available to heat the products, an upper limit to the flame temperature can be determined. This temperature is usually referred to as the adiabatic flame temperature.

First, subtract the ash to derive the composition of the fuel actually burned,

$$n_1 = n_1 - \left(\frac{\dot{M}_{ASH}}{\dot{M}_{FUEL,DRY}} \right) \times \text{(moles of carbon in ash)}$$

etc.

Air supplied to the flame is one of the independent variables affecting incinerator performance. The coefficient n_6 of Equation 1 is determined directly from the underfire airflow to the flame. Once the fuel composition and the air (oxygen) have been established, Equation 1 is balanced using the method described above.

Subtracting the energy lost vaporizing the moisture in the fuel,

$$\hat{Q}_{LOST} = \text{(Mass fraction of moisture in fuel) x (heat of vaporization of water at a pressure of 1 atmosphere)}$$

The net heat released to the flame can be calculated,

$$\dot{q}_{FLAME} = \left(n_7\, Q_{CO_2} + n_8\, Q_{H_2O} + n_9\, Q_{CO} - Q_{FUEL}{}^{*} - \hat{Q}_{LOST} \right) \dot{M}_{FUEL,\ DRY}$$

and, since the mass flow through the flame is known,

$$\dot{M}_{FLAME} = \dot{M}_{FUEL,\ WET} + \dot{M}_{AIR} - \dot{M}_{ASH}$$

The adiabatic flame temperature can be determined by application of conservation of energy,

$$T_{FLAME} = T_{DATUM} + \left[\dot{q}_{FLAME} + \dot{M}_{FUEL,DRY}\, \Delta h_{FUEL}\, (T_\infty) + \dot{M}_{AIR}\, C_{P,AIR}\, (T_\infty)\, \Delta T_\infty \right] \Big/ \left[\dot{M}_{FLAME}\, C_{P,MIX}\, (T_{FLAME}) + C_{P,ASH}\, \dot{M}_{ASH} \right] \qquad (2)$$

where: T_{DATUM} = reference temperature of defined properties

$C_p(T)$ = specific heat at temperature T

$\Delta T_\infty = T_\infty - T_{DATUM}$

$\Delta h(T)$ = enthalphy at temperature T relative to T_{DATUM}

$$C_{P,MIX} = \sum_{MIXTURE} (\text{mole fraction} \times C_{P,MEAN})$$

*For most fuels, $Q_{FUEL} < 0$.

$$C_{P,MEAN}(T_2) \equiv \frac{1}{T_2 - T_{DATUM}} \int_{T_{DATUM}}^{T_2} C_P(T)\, dT$$

Note that the temperature dependency of specific heat* makes Equation 2 nonlinear. The relationships of Sweigert and Beardsley (Ref 13) were used to calculate specific heats as a function of temperature. These relationships and Equation 2 were solved simultaneously.

PRIMARY COMBUSTION CHAMBER TEMPERATURES

Temperatures in the primary combustion chamber are calculated by solving the energy equations governing the flame front, the combustion chamber interior, and the walls of the primary combustion chamber (PCC). Combustion products in both the flame and the PCC interior are assumed to be perfectly mixed. The homogeneous flame temperature derived in this manner can be considered a lower limit to the actual flame temperature.

The flame composition is already known from the adiabatic calculations. Composition of the combustion products in the primary combustion chamber is determined in an analogous manner, taking into account oil injected into the chamber, overfire air, and possible air leakage.

If underfire air is insufficient for the complete combustion of the fuel (wastes) and the oil, PCC air leakage will induce further chemical reaction and, thus, energy released in the primary combustion chamber,

$$\dot{q}_{PCC} = \left(n_7\, Q_{CO_2} + n_8\, Q_{H_2O} + n_9\, Q_{CO} - Q_{FUEL} - Q_{OIL} - \hat{Q}_{LOST} \right) \dot{M}_{FUEL,DRY} - \dot{q}_{FLAME}$$

Energy terms included in the PCC analyses are illustrated schematically in Figure C-1.

Applying conservation of energy to the flame,**

$$\dot{M}_{FLAME}\, C_{P,MIX}(T_{FLAME})\, \Delta T_{FLAME} + \dot{M}_{ASH}\, C_{P,ASH}\, \Delta T_{FLAME} + \dot{q}_{RAD,F\rightarrow W} + \dot{q}_{RAD,F\rightarrow G} - \dot{q}_{FLAME} - \dot{M}_{FUEL,DRY}\, \Delta h_{FUEL}(T_\infty)$$

*The specific heat of ash is assumed to be a constant.

**The flame is considered to be the region influenced by underfire air. It does not touch the PCC walls (i.e., there is no convection heat transfer between the flame and the walls).

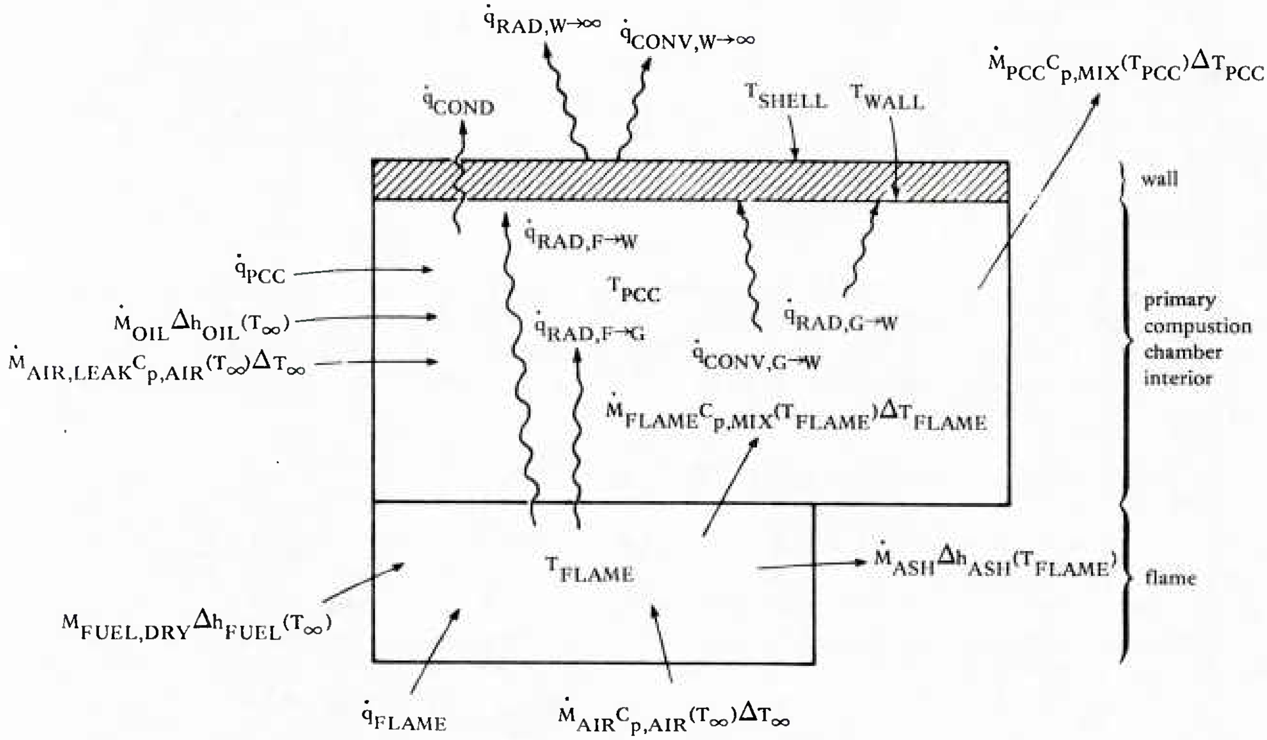

Figure C-1. Conservation of energy in primary combustion chamber.

$$- \dot{M}_{AIR} \, C_{P,AIR}(T_\infty) \, \Delta T_\infty = 0 \tag{3}$$

where: $\dot{q}_{RAD,F \to W}$ = radiation from flame to walls of PCC

$$= A_{FLAME} \, \sigma \left\{ \left[1 - \varepsilon_{MIX}(T_{FLAME}) \right] T^4_{FLAME} - \left[1 - \varepsilon_{MIX}(T_{WALLS}) \right] T^4_{WALLS} \right\}$$

$\dot{q}_{RAD,F \to G}$ = radiation from flame to products of combustion inside the PCC

$$= A_{FLAME} \, \sigma \left[\varepsilon_{MIX}(T_{FLAME}) \, T^4_{FLAME} - \varepsilon_{MIX}(T_{PCC}) \, T^4_{PCC} \right]$$

T_{FLAME} = homogeneous flame temperature

T_{PCC} = homogeneous temperature of products of combustion in PCC

T_{WALLS} = PCC inside wall temperature

A_{FLAME} = surface area of flame front

σ = Stefan-Boltzmann constant

Both the flame and inside of the PCC walls are assumed to act as black bodies. The products of combustion are assumed gray; the emissivities of these gases, $\varepsilon_{MIX}(T)$, are derived by curve fitting the data of Hottel et al. (Ref 14). Gas emissivities are thus a function of both composition and temperature. The configuration factor from the flame to the PCC walls is assumed to be one.

Applying conservation of energy to the interior of the primary combustion chamber,

$$\dot{M}_{PCC}\, C_{P,MIX}(T_{PCC})\, \Delta T_{PCC} + \dot{q}_{RAD,G\rightarrow W} + \dot{q}_{CONV,G\rightarrow W}$$

$$- \dot{q}_{PCC} - \dot{q}_{RAD,F\rightarrow G} - \dot{M}_{FLAME}\, C_{P,MIX}(T_{FLAME})\, \Delta T_{FLAME}$$

$$- \dot{M}_{OIL}\, \Delta h_{OIL}(T_\infty) - \dot{M}_{AIR,LEAK}\, C_{P,AIR}(T_\infty)\, \Delta T_\infty = 0 \qquad (4)$$

where: $\dot{q}_{RAD,G\rightarrow W}$ = radiation from combustion gases to PCC walls

$$= A_{PCC}\, \sigma \left[\varepsilon_{MIX}(T_{PCC})\, T_{PCC}^4 - \varepsilon_{MIX}(T_{WALLS})\, T_{WALLS}^4 \right]$$

$\dot{q}_{CONV,G\rightarrow W}$ = convection heat transfer to PCC wall interior

$= h_{CONV,PCC}\, A_{PCC}(T_{PCC} - T_{WALLS})$

A_{PCC} = surface area of PCC walls

$h_{CONV,PCC}$ = convection film coefficient

Finally, applying conservation of energy to the walls,

$$\dot{q}_{COND} - \dot{q}_{RAD,F\rightarrow W} - \dot{q}_{RAD,G\rightarrow W} - \dot{q}_{CONV,G\rightarrow W} = 0 \qquad (5)$$

$$\dot{q}_{RAD,W\rightarrow\infty} + \dot{q}_{CONV,W\rightarrow\infty} - \dot{q}_{COND} = 0 \qquad (6)$$

where: $\dot{q}_{COND}$ = conduction heat transfer through the walls

$= KA_{PCC}(T_{WALLS} - T_{SHELL})$

$\dot{q}_{CONV,W\rightarrow\infty}$ = convection off outer surface of PCC walls

$= h_{CONV,\infty}\, A_{PCC}(T_{SHELL} - T_\infty)$

$\dot{q}_{RAD,W\to\infty}$ = radiation off outer surface of PCC walls

$$= A_{PCC}\sigma\, \varepsilon_{SHELL}(T^4_{SHELL} - T^4_{\infty})$$

T_{SHELL} = temperature of outer skin of PCC

ε_{SHELL} = emissivity of outer skin of PCC

K = conductance of PCC walls

Equations 3 through 6, along with the relationships derived for temperature variations of specific heat and emissivity, are solved simultaneously for the temperatures T_{FLAME}, T_{PCC}, T_{WALLS}, and T_{SHELL}.

SECONDARY COMBUSTION CHAMBER TEMPERATURES

Temperatures of the combustion products and walls in the secondary combustion chamber are calculated in a manner analogous to the PCC problem. The energy equations governing the interior of the secondary combustion chamber (SCC), the inner walls, and outer skin are solved simultaneously while allowing both specific heat and emissivity to vary with temperature. If combustion is not completed in the PCC, secondary air will induce further chemical reactions and requires an additional heat source term in the energy equation governing the SCC interior.

HEAT RECOVERY BOILER

The boiler unknowns are the steam generated, the total heat transferred between the combustion products and the feed water/steam, and the temperature of the combustion gases as they enter the stack. Temperature and pressure of the feed water and steam are assumed to be known.

Waterwalls are simulated by setting the combustion chamber inner wall temperature equal to the steam temperature (i.e., ignoring the very small temperature gradients through the metal of the waterwalls and through the boundary layer on the feed water/steam side of the system). Heat transfer to these walls is already a part of the analysis of the PCC; steam generation merely involves bookkeeping the heat fluxes to the waterwalls.

Modeling a convection boiler is more complex. It is accomplished by applying conservation of energy to the combustion gases, the feed water/steam, and to the overall heat recovery boiler (individual energy terms are illustrated in Figure C-2),

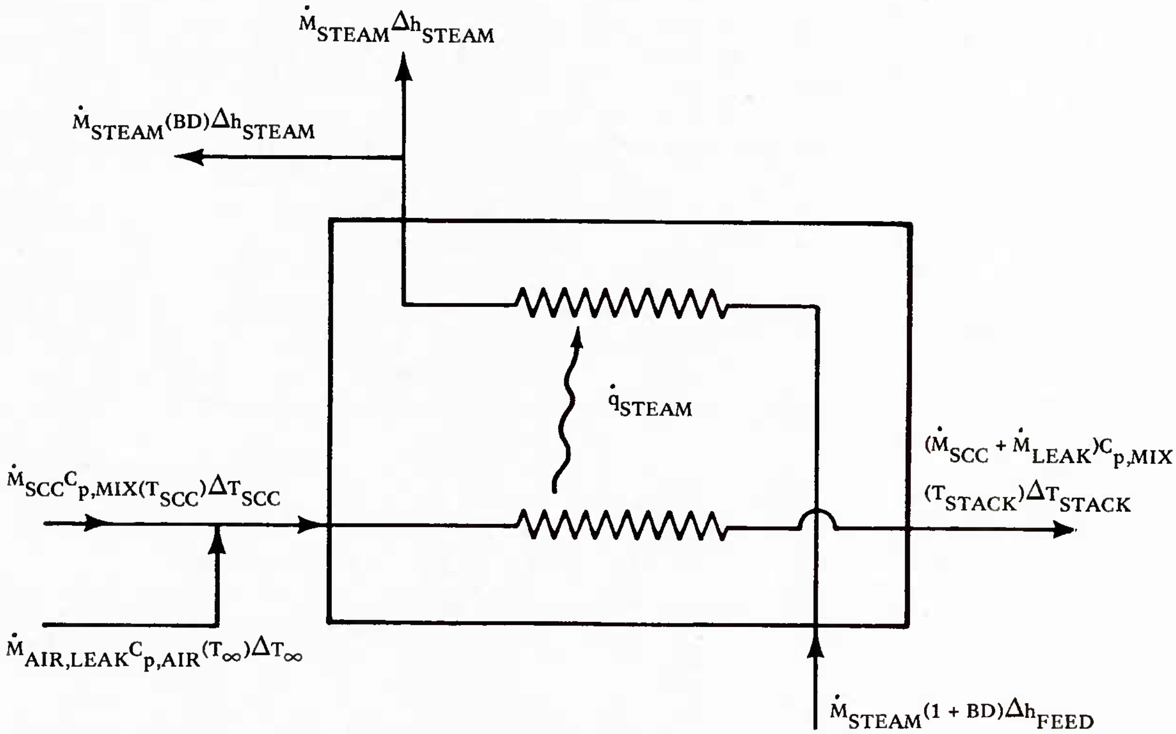

Figure C-2. Conservation of energy in energy recovery boiler.

$$(\dot{M}_{SCC} + \dot{M}_{AIR,LEAK})\, C_{P,MIX}(T_{STACK})\, \Delta T_{STACK}$$

$$+ \dot{q}_{STEAM} - \dot{M}_{SCC}\, C_{P,MIX}(T_{SCC})\, \Delta T_{SCC}$$

$$- \dot{M}_{AIR,LEAK}\, C_{P,AIR}(T_\infty)\, \Delta T_\infty = 0 \tag{7}$$

$$\dot{M}_{STEAM}\, \Delta h_{STEAM}(T_{STEAM}) + BD\, \dot{M}_{STEAM}\, \Delta h_{STEAM}\, (T_{STEAM})$$

$$- \dot{q}_{STEAM} - (1 + BD)\, \dot{M}_{STEAM}\, \Delta h_{FEED}(T_{FEED}) = 0 \tag{8}$$

$$\dot{q}_{STEAM} - U_{MEAN}(\dot{M},T)\, A_{BOILER}\, LMTD = 0 \tag{9}$$

where:

$\dot{M}_{SCC}$ = mass flow out of the secondary combustion chamber

$\dot{M}_{AIR,\ LEAK}$ = air leakage down the dump stack

$\dot{M}_{STEAM}$ = steam generated in the boiler

BD = boiler blowdown as a fraction of steam generated

$\Delta h_{FEED}(T_{FEED})$ = enthalpy of feed water at temperature T_{FEED} relative to T_{DATUM}

$\Delta h_{STEAM}(T_{STEAM})$ = enthalpy of steam at T_{STEAM} relative to T_{DATUM}

$\dot{q}_{STEAM}$ = heat transferred between combustion products and feed water/steam

T_{SCC} = homogeneous temperature of products of combustion in SCC

T_{STEAM} = temperature of the steam exiting the boiler

T_{STACK} = stack gas temperature (i.e., temperature of combustion gases as they exit the boiler)

A_{BOILER} = total surface area of boiler tubes

LMTD = logarithmic mean overall temperature difference, Figure C-2

$$\equiv \frac{(T_{SCC} - T_{STEAM}) - (T_{STACK} - T_{FEED})}{\ln \dfrac{T_{SCC} - T_{STEAM}}{T_{STACK} - T_{FEED}}}$$

The boiler overall heat transfer coefficient, $U_{MEAN}(\dot{M},T)$, varies with both temperature and flow rate. The magnitude of this coefficient is determined by noting that the resistance to heat transfer from the combustion gases is the dominant resistance and, thus, only gas properties have an appreciable effect on U_{MEAN}. A staggered tube configuration (Ref 14) is assumed,

$$N_{Nu} \propto N_{Re}^{0.6} \; N_{Pr}^{0.33}$$

where: N_{Nu} = Nusselt number

N_{Re} = Reynolds number

N_{Pr} = Prandtl number

Observing that the variation in the one-third power of the Prandtl number is negligible, and lumping the geometry into the constant of proportionality, $\bar{U}$,*

---

*$\bar{U}$ is back-calculated from boiler performance data that are part of the input.

$$U_{MEAN} = \bar{U}\, k_{AVG}(T_{AVG}) \left[\frac{\dot{M}_{SCC} + \dot{M}_{AIR\ LEAK}}{\mu_{AVG}(T_{AVG})} \right]^{0.6} \tag{10}$$

where: $T_{AVG} = (1/4)\,(T_{SCC} + T_{STACK} + T_{FEED} + T_{STEAM})$

$k_{AVG}(T_{AVG})$ = thermal conductivity of combustion products at the average temperature T_{AVG}

$\mu_{AVG}(T_{AVG})$ = viscosity of combustion products at temperature T_{AVG}

$$k_{AVG}, \mu_{AVG} \propto \frac{T_{AVG}^{1.5}}{225 + T_{AVG}} \tag{11}$$

Equations 11 are usually referred to as the Eucken equations and were derived using the methods of the kinetic theory (Ref 15). For this simulation, the constants of proportionality are determined by assuming that the products of combustion behave in the same manner as air.

Equations 7 through 11 are solved simultaneously.

NUMERICAL METHODS

The numerics involved in the simulation are straightforward. The only portions of the program that might be difficult to follow are those sections involving the simultaneous solution of the component energy equations (e.g., Equations 3 through 6). Variable properties make these equations nonlinear; an iterative technique is necessary. The Newton-Raphson iteration (Ref 16) was selected for this application.

With this technique, an initial estimate is made of the value of the unknowns, e.g.,

$T_1 = T_{FLAME} \sim 3{,}500°R$

$T_2 = T_{PCC} \sim 3{,}200°R$

$T_3 = T_{WALLS} \sim 3{,}000°R$

$T_4 = T_{SHELL} \sim 1{,}000°R$

A Jacobian of the energy equations is formed,

$$F_1 = F_1(T_1, T_2, T_3, T_4) = 0$$

$$F_2 = F_2(T_1, T_2, T_3, T_4) = 0$$

$$F_3 = F_3(T_1, T_2, T_3, T_4) = 0$$

$$F_4 = F_4(T_1, T_2, T_3, T_4) = 0$$

$$[J] \equiv \begin{bmatrix} \frac{\partial F_1}{\partial T_1} & \frac{\partial F_1}{\partial T_2} & \frac{\partial F_1}{\partial T_3} & \frac{\partial F_1}{\partial T_4} \\ \frac{\partial F_2}{\partial T_1} & \frac{\partial F_2}{\partial T_2} & \frac{\partial F_2}{\partial T_3} & \frac{\partial F_2}{\partial T_4} \\ \frac{\partial F_3}{\partial T_1} & \frac{\partial F_3}{\partial T_2} & \frac{\partial F_3}{\partial T_3} & \frac{\partial F_3}{\partial T_4} \\ \frac{\partial F_4}{\partial T_1} & \frac{\partial F_4}{\partial T_2} & \frac{\partial F_4}{\partial T_3} & \frac{\partial F_4}{\partial T_4} \end{bmatrix}$$

inverted,

$$[J] = [J]^{-1}$$

and used to improve the initial estimate,

$$T_i = T_i - \sum_{j=1}^{n} J_{i,j} \cdot F_j$$

For example,

$$T_{FLAME} = 3500 - \sum_{j=1}^{4} \left(J_{1,j} \cdot F_j\right)$$

This improved estimate now replaces the initial estimate; the variable properties, specific heat and emissivity, are updated based upon the new temperatures, and the calculations are repeated, producing a still better estimate of the unknowns. The iteration continues until some preset limit to the number of iterations is reached or until the change in the calculated value of all the unknowns is less than some preset tolerance.

VALIDATION OF MODEL

The most credible method of determining the accuracy of a model is to compare predicted values with corresponding experimental data. When incinerators are being modeled, however, such a comparison is difficult because of the extensive data required and because many necessary measurements are not easily obtained (e.g., fuel composition, feed rate, and combustion and leakage airflows). No incinerator data, sufficient to validate all the model's options, have been published.

The evaluation tests of the energy recovery incinerator at the Naval Station, Mayport, Florida (Ref 17), are probably the most comprehensive. This incinerator is an excess air device with a single pass water tube boiler located downstream from the secondary combustion chamber as shown schematically by Figure C-3. Key data are also included: arithmetic averages of the 24 hourly readings taken on 9 Dec 1980.

Ultimate and proximate analyses of the waste were conducted once. The only gas flow measured was the total mass flow out the stack, but this variable was monitored continuously. SCC combustion air was set at 20% in excess of the air required to stoichiometrically burn SCC oil. Oil consumption was monitored, and airflow to the PCC, including infiltration, was determined by subtraction. The underfire/overfire split was ratioed on the basis of blower capacities. All other inputs and steam generation were measured directly and continuously.

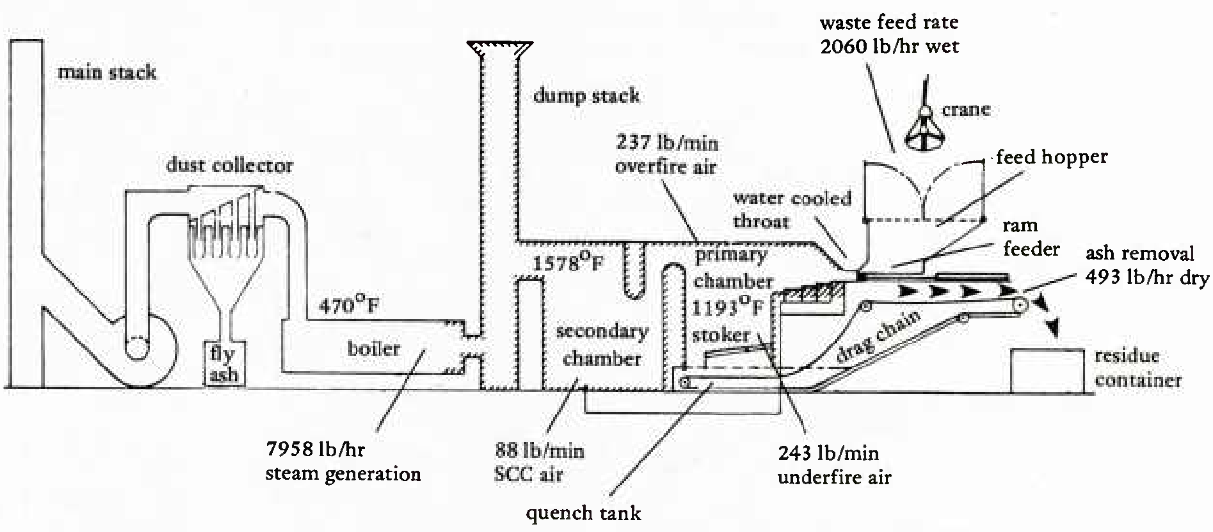

Figure C-3. Cross section of incineration heat recovery system at the Naval Station, Mayport, Florida (Ref 17).

Table C-1 is a comparison of the predicted and measured performance of the Mayport incinerator. This table provides an indication of the capability of the model to simulate excess air operation and to predict steam generation when a convection boiler is used. In addition, the mass and energy transfer calculations leading to the prediction of an energy recovery efficiency are common to all configurations.

Tests conducted at the National Bureau of Standards (Ref 8) suggest that the starved air combustion of solid wastes in an incinerator is diffusion controlled. In a diffusion flame, part of the waste (actually the products of the pyrolysis of the waste) would burn completely to water vapor and carbon dioxide, as much as the air supply would allow, and the rest would remain unchanged. This mechanism is mathematically very simple; the energy released and the quantities of the combustion products are linearly proportional to the air supplied.

The other extreme is the equilibrium flame (i.e., combustion is controlled by chemical reaction rates). The energy released and the composition of the combustion products are a complex function of temperatures, available oxygen, and the chemical composition of the waste.

A modified diffusion flame mechanism is built into the model. Rather than being oxidized directly to carbon dioxide, carbon is assumed to burn in stages, with carbon monoxide formed initially. If additional air is available, the carbon monoxide is oxidized to form carbon dioxide. Carbon normally burns in such a manner (Ref 9), and this modification was made to improve the predicted composition of the combustion products.

Table C-1. Comparing HRI Predictions With the Measured Performance of the Incinerator at the Naval Station, Mayport, Florida

Variable	Measured Value[a] 9 Dec 1980	HRI Prediction
PCC gas temperature, °F	1,193	1,163
PCC outside wall temperature, °F	175	197
SCC gas temperature, °F	1,578	1,499
SCC outside wall temperature, °F	221	224
Stack gas temperature, °F	470	509
Steam generation, lb/hr	7,958	8,657
Overall efficiency	0.49	0.48

[a]Reference 17.

The energy released during starved air combustion is examined in Figures C-4 and C-5 with the combustion mechanism as a parameter. (Equilibrium compositions were determined using the program of Reference 18). When burning cellulose, the major ingredient in most types of solid waste, differences in the energy released are negligible. With plastic, differences are small. Thus, the model can be expected to accurately predict the energy released during starved air incineration regardless of the validity of the assumed combustion mechanism.

A validation of the predicted waterwall performance is more difficult and cannot be made using theoretical arguments. A comparison with data is necessary. Heat transfer to the waterwalls is the critical parameter, and the data must be comprehensive enough to separate the convective and radiative components of the heat flux. Emissivity calculations become very important; the program must adequately predict gas compositions, a problem particularly severe for starved air operation. Examination of the accuracy of the waterwall simulation will be postponed.

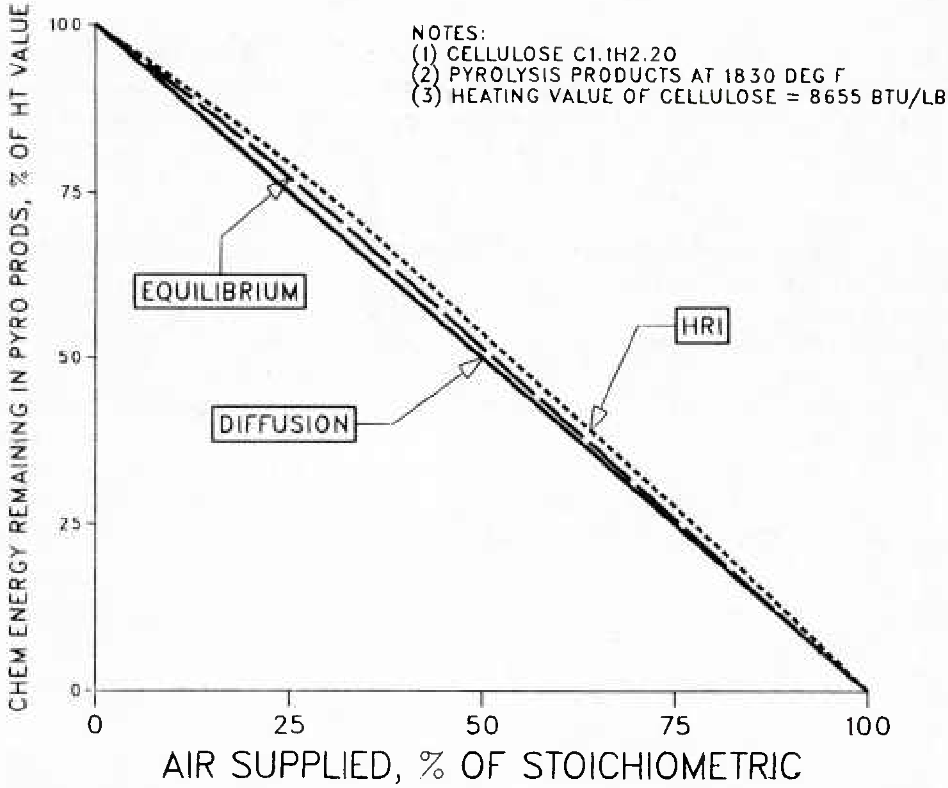

Figure C-4. **Comparison of equilibrium and diffusion models in predicting the progress of starved air combustion of cellulose.**

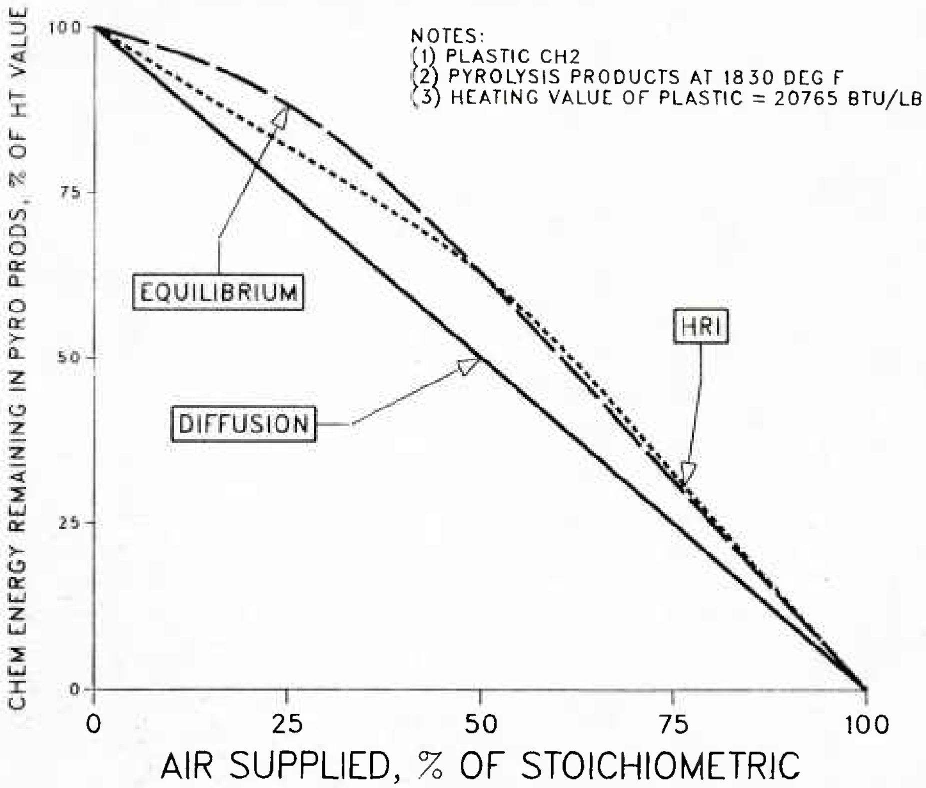

Figure C-5. **Comparison of equilibrium and diffusion models in predicting the progress of starved air combustion of plastic.**

Appendix D

EFFICIENCY CRITERIA USED TO DEFINE PERFORMANCE OF ENERGY RECOVERY INCINERATORS (Ref 4)

The performance of the heat recovery incinerator was evaluated by applying the heat loss method suggested for steam generating units by the American Society of Mechanical Engineers (Ref 11). "The efficiency is equal to 100% minus a quotient expressed in percent. The quotient is made up of the sum of all accountable losses as the numerator, and heat in the fuel plus heat credits as the denominator." Or, in mathematical form, Equation 2,

$$\eta \equiv 1 - \frac{\Sigma \text{ LOSSES}}{\Sigma \text{ INPUT}}$$

Not all losses are included in the summations, and some are slightly different from those suggested by Reference 11 to be compatible with the mathematical simulation.

LOSSES

Heat lost vaporizing moisture with waste $= \dot{M}_{MOIST} \, \Delta h_{fg}$

Vaporization of water generated by burning hydrogen in waste

$$= 18 \, n_2 \, \Delta h_{fg} \, \dot{M}_{FUEL}$$

Carbon carried out with ash $= \dot{M}_{ASH} \, C_{ASH} \, Q_{CO_2}$

Sensible heat in ash $= C_{P,ASH} \, \dot{M}_{ASH} \, \Delta T_{FLAME}$

Heat transfer through walls of PCC $= KA_{PCC}(T_{PCC,WALLS} - T_{PCC,SHELL})$

Heat transfer through walls of SCC $= KA_{SCC}(T_{SCC,WALLS} - T_{SCC,SHELL})$

Incomplete combustion $= \dot{M}_{FUEL}[n_9(Q_{CO_2} - Q_{CO}) + n_{12} \, Q_{CO_2} + n_{11} \, Q_{H_2O}]$

Sensible heat in stack gases

$$= (\dot{M}_{SCC} + \dot{M}_{AIR,LEAK}) \, C_{P,MIX}(T_{STACK}) \, \Delta T_{STACK}$$

Loss of steam due to blowdown $= \dot{M}_{STEAM}\,[BD/(1 - BD)]\,\Delta h_{STEAM}(T_{STEAM})$

INPUTS

Chemical plus sensible energy in waste

$$= \dot{M}_{FUEL}\,HHV_{FUEL,DRY} - \dot{M}_{AIR}\,C_{P,AIR}(T_\infty)\,\Delta T_\infty + (\dot{M}_{SCC} + \dot{M}_{AIR,LEAK})\,C_{P,AIR}(T_\infty)\,\Delta T_\infty$$

Enthalpy of combustion air $= \dot{M}_{AIR}\,C_{P,AIR}(T_\infty)\,\Delta T_\infty$

Chemical plus sensible energy in oil $\cong \dot{M}_{OIL}\,HHV_{OIL}$

Enthalpy of boiler feed water $= \dot{M}_{STEAM}(1 + BD)\,\Delta h_{FEED}(T_{FEED})$

Sensible heat of products of combustion entering boiler

$$= (\dot{M}_{SCC} + \dot{M}_{AIR,LEAK})\,C_{P,MIX}(T_{SCC})\,\Delta T_{SCC}$$

The power required to run accessories is input directly.

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